Ultrashort Pulse (USP) Laser – Matter Interactions

Integrity ★ Service ★ Excellence

5 MAR 2013

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Program Officer

AFOSR/RTB

Air Force Research Laboratory

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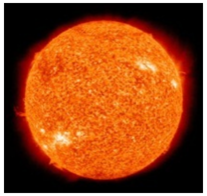
Modelocked femtosecond lasers


Wikipedia

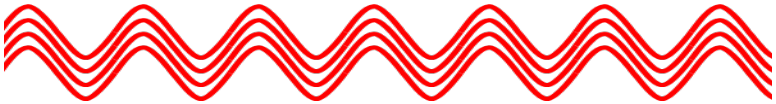
Sunlight


Wikipedia

Light Emitting Diode

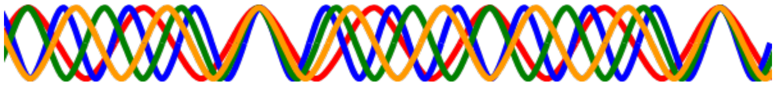

Newport

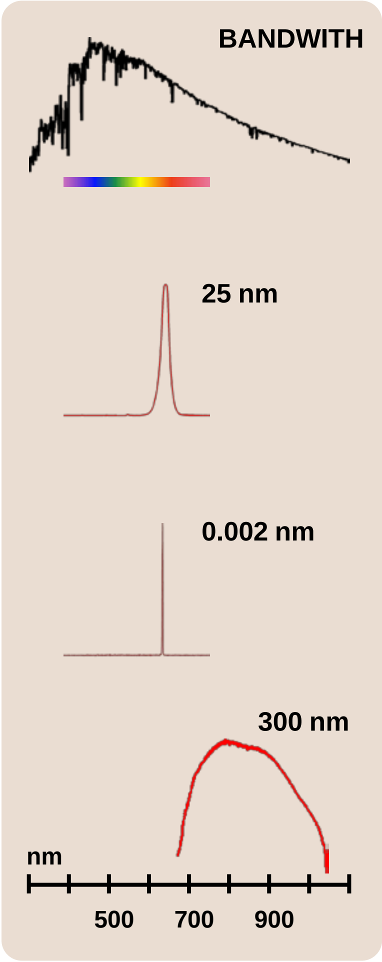
He-Ne cw laser

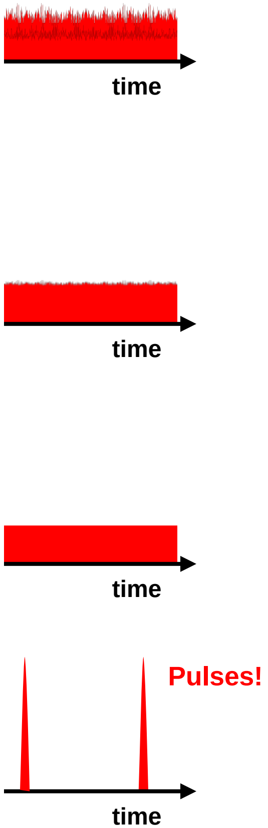



ThorLabs

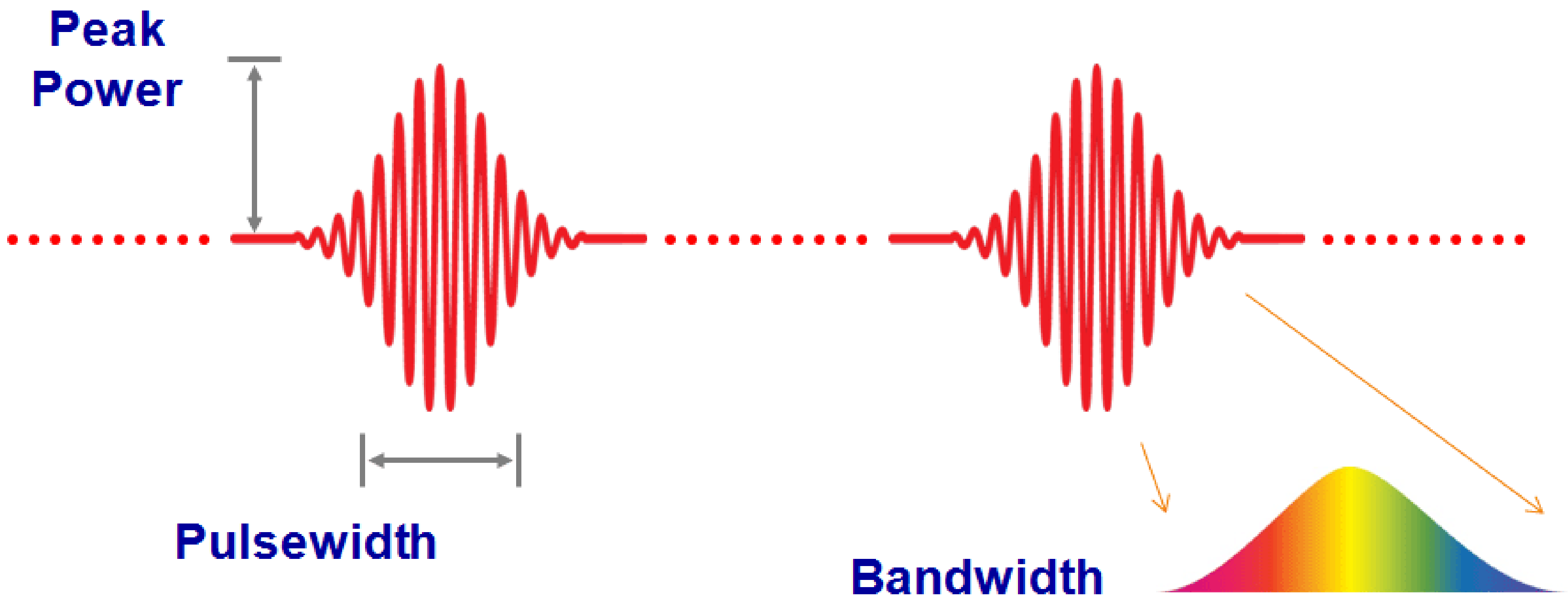
Ti:Sapphire modelocked fs laser







2013 AFOSR SPRING REVIEW
3001O PORTFOLIO OVERVIEW

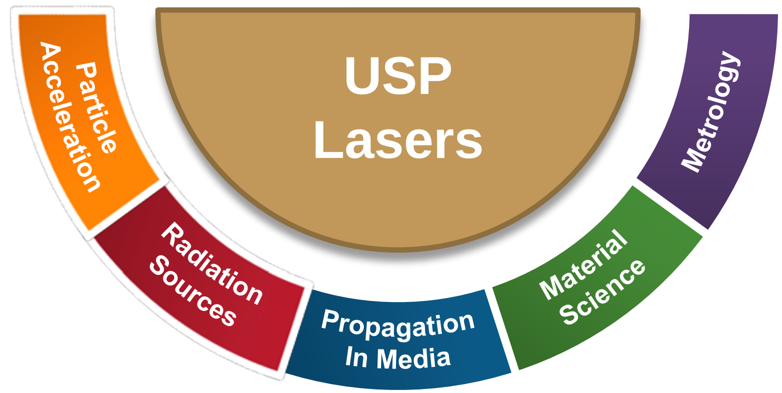


- **The program aims to understand and control light sources exhibiting extreme bandwidth, peak power and temporal characteristics.**
- **Portfolio sub-areas: optical frequency combs, high-field science, attosecond physics.**

Applications of USP Lasers

Particle Acceleration
ultrahigh electric field gradients

- Table-top GeV electron accelerators
- MeV ion sources for imaging
- Isotope production
- Hadron tumor therapy
- Proton-based fast ignition



Metrology
stabilized, ultra-wide bandwidth

- Ultra-stable freq sources
- Optical waveform synthesis
- High precision spectroscopy
- Frequency/time transfer
- High-capacity comms
- Coherent LIDAR
- Optical clocks
- Calibration

Secondary Radiation Sources
generation of particle & photons

- High power THz generation
- Extreme ultraviolet lithography
- Biological soft x-ray microscopy
- Non-destructive evaluation
- Medical imaging/therapy

Propagation in media
self-channeling

- Remote sensing
- Remote tagging
- Directed energy
- Electronic warfare
- Countermeasures
- Advanced sonar

Material Science
ultrashort, high peak power

- Surgery
- Chemical analysis (LIBS)
- Surface property modification
- Non-equilibrium ablation
- Micromachining
- Ultrafast photochemistry
- Attochemistry

Outline

– Microresonator-based optical frequency combs

– High peak power, ultrashort pulse laser processing of materials

– Extreme ultraviolet (EUV) comb spectroscopy

– High harmonic interferometry

– Relativistic optics

Photo credits: DOI: 10.1038/nature05524, www.attoworld.de, E. Chowdhury (OSU)

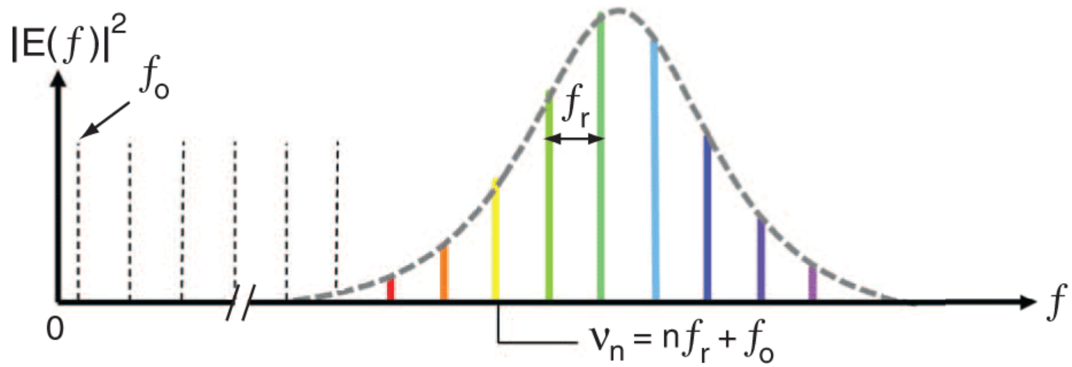
Outline

- FREQ – Microresonator-based optical frequency combs
- TIME – High peak power, ultrashort pulse laser processing of materials
- FREQ – Extreme ultraviolet (EUV) comb spectroscopy
- TIME – High harmonic interferometry
- PEAK – Relativistic optics

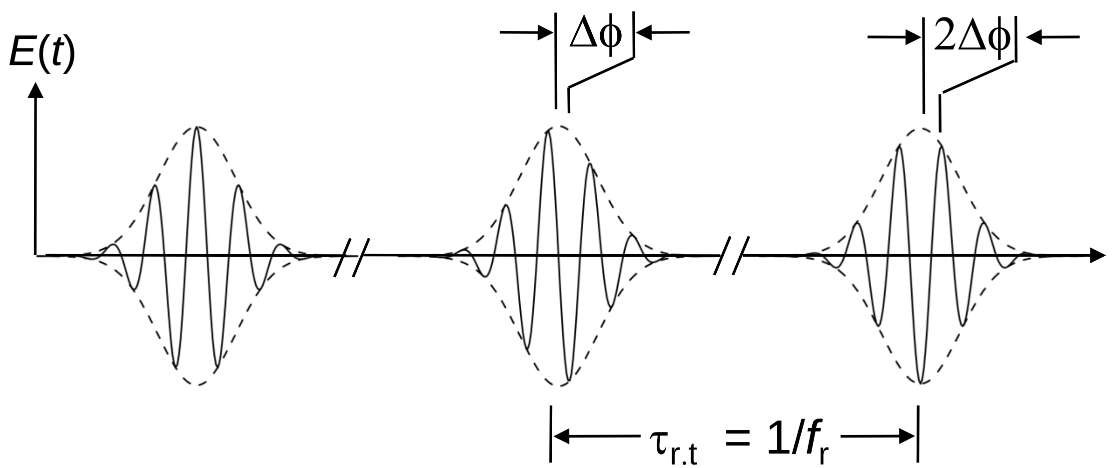
Photo credits: DOI: 10.1038/nature05524, www.attoworld.de, E. Chowdhury (OSU)

Optical frequency combs: Frequency & time domains

Frequency domain

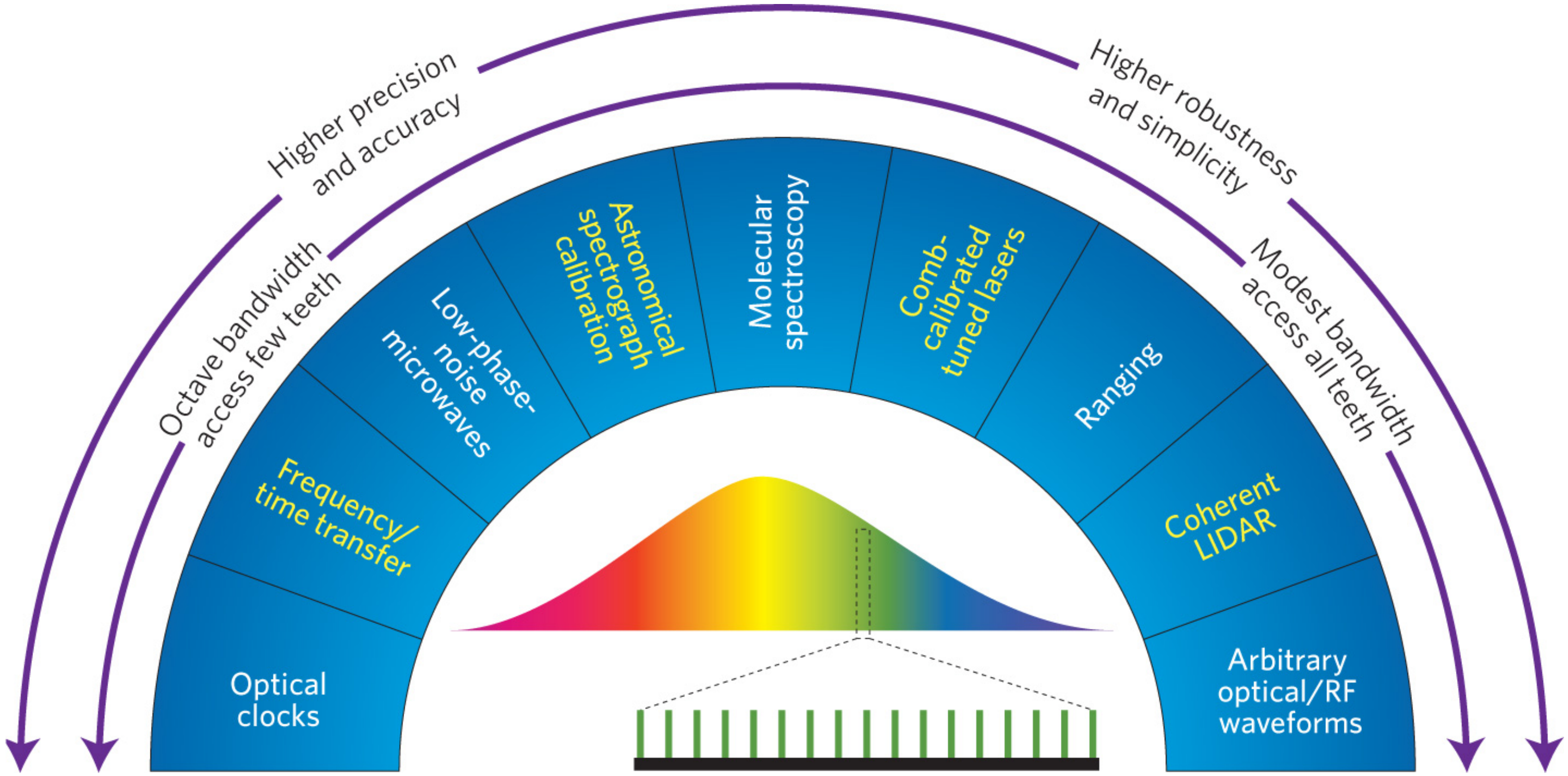


Time domain



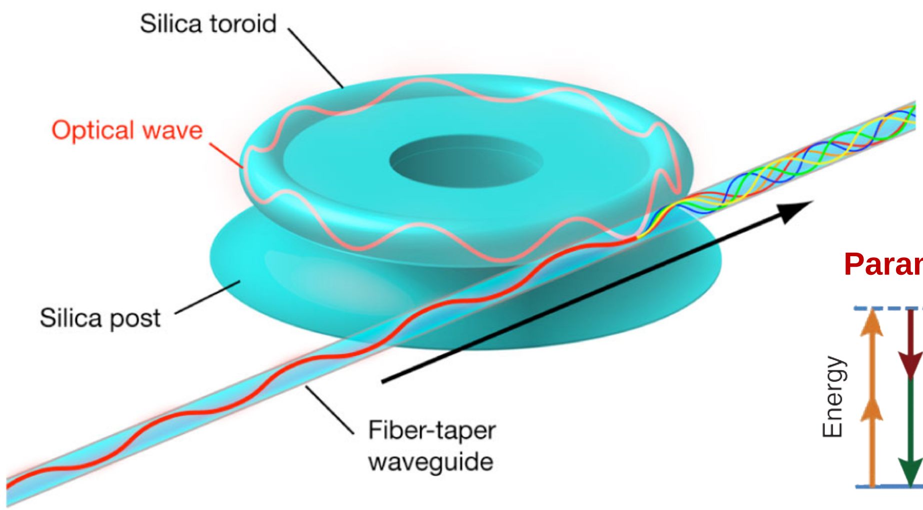
Source: Kippenberg et al., Science (2011); Diddams.

Metrological applications of optical frequency combs

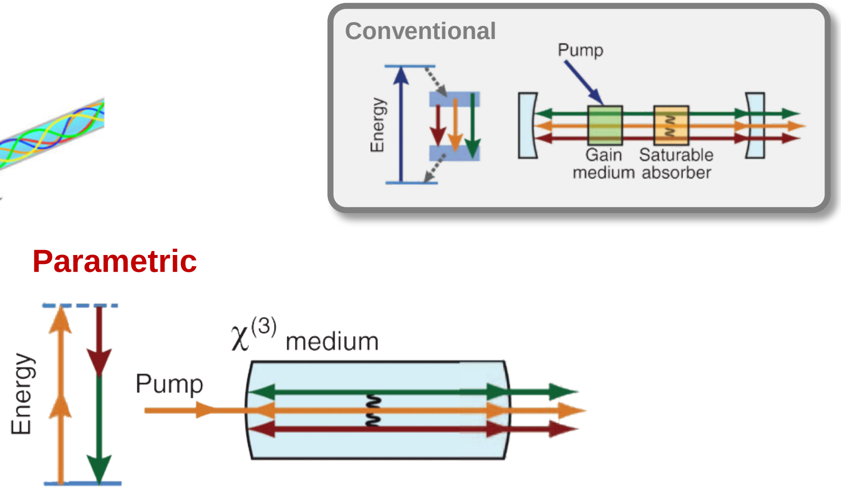


Combs in monolithic microresonators

Source: Braje, Physics 3, 75 (2010)

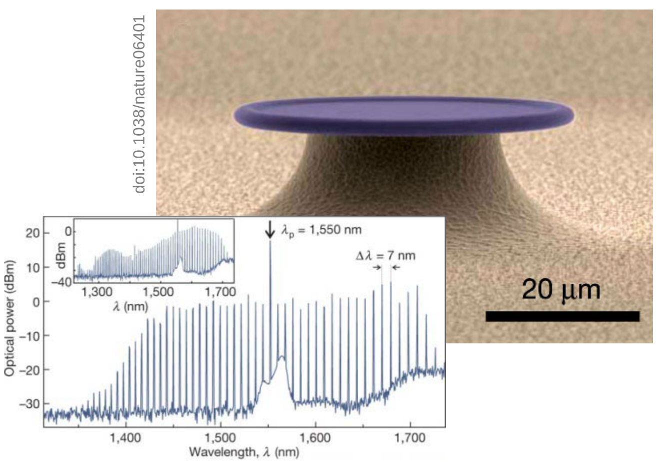


Source: Kippenberg et al., Science (2011)

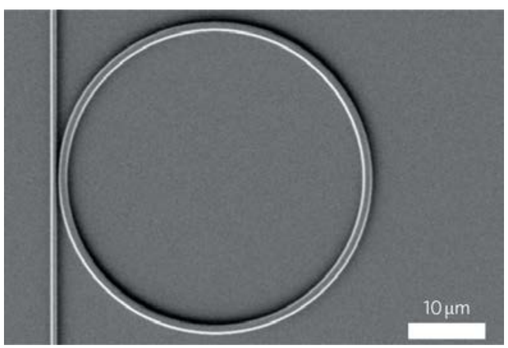


Silica toroids

doi:10.1038/nature06401

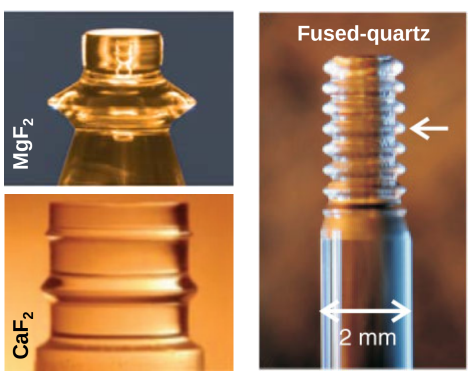


Silicon nitride microrings



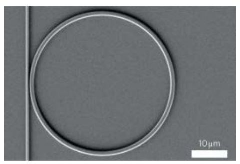
doi: 10.1038/nphoton.2009.259

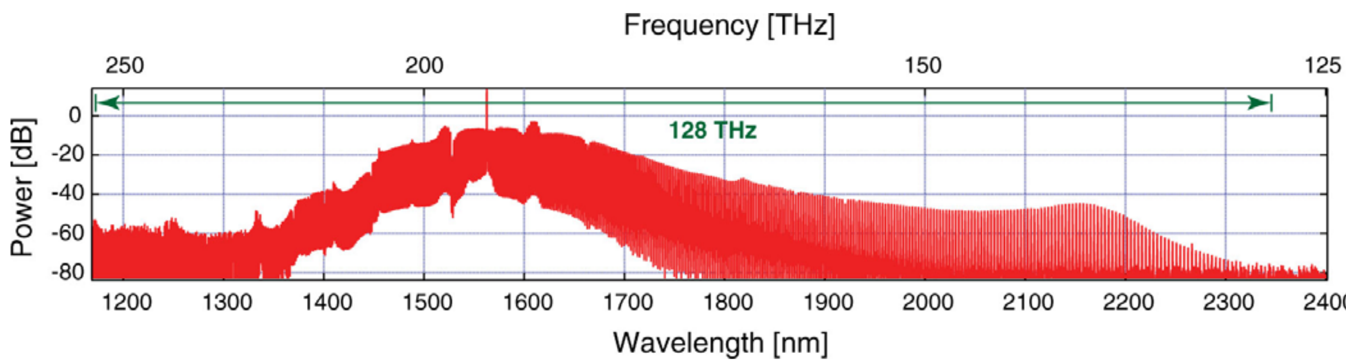
High-Q mm crystalline resonators

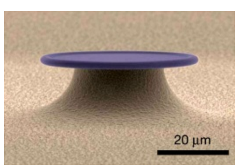


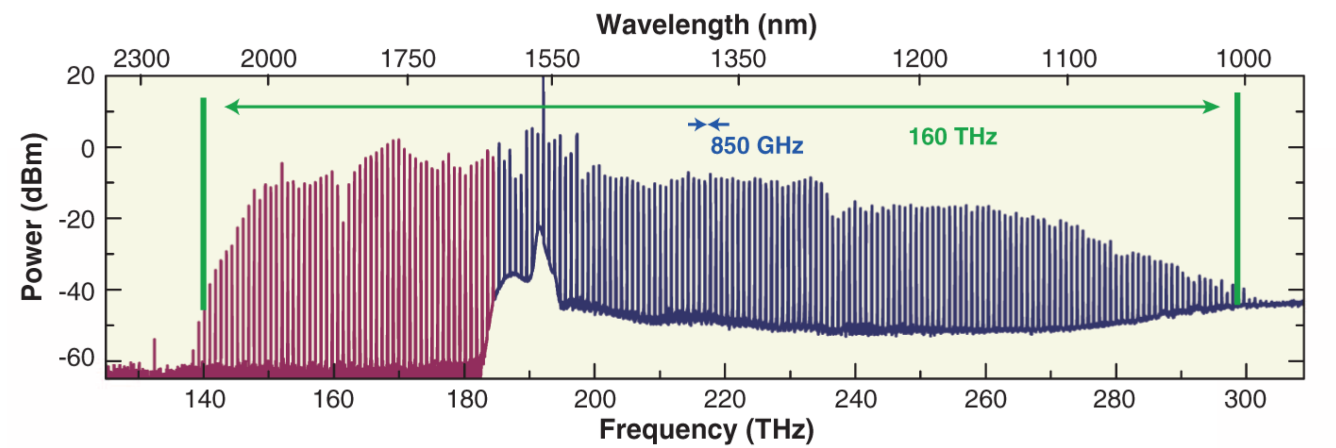
top left doi: 10.1038/nphoton.2012.127
right doi: 10.1103/physreva.84.053833
bottom left doi: 10.1103/physrevlett.101.093902

Octave spanning bandwidths



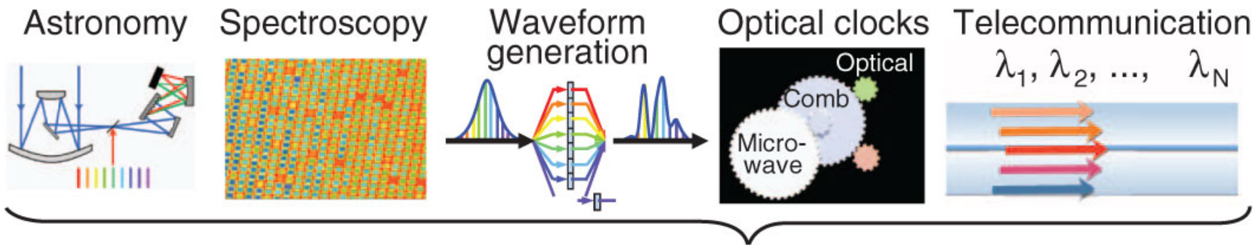


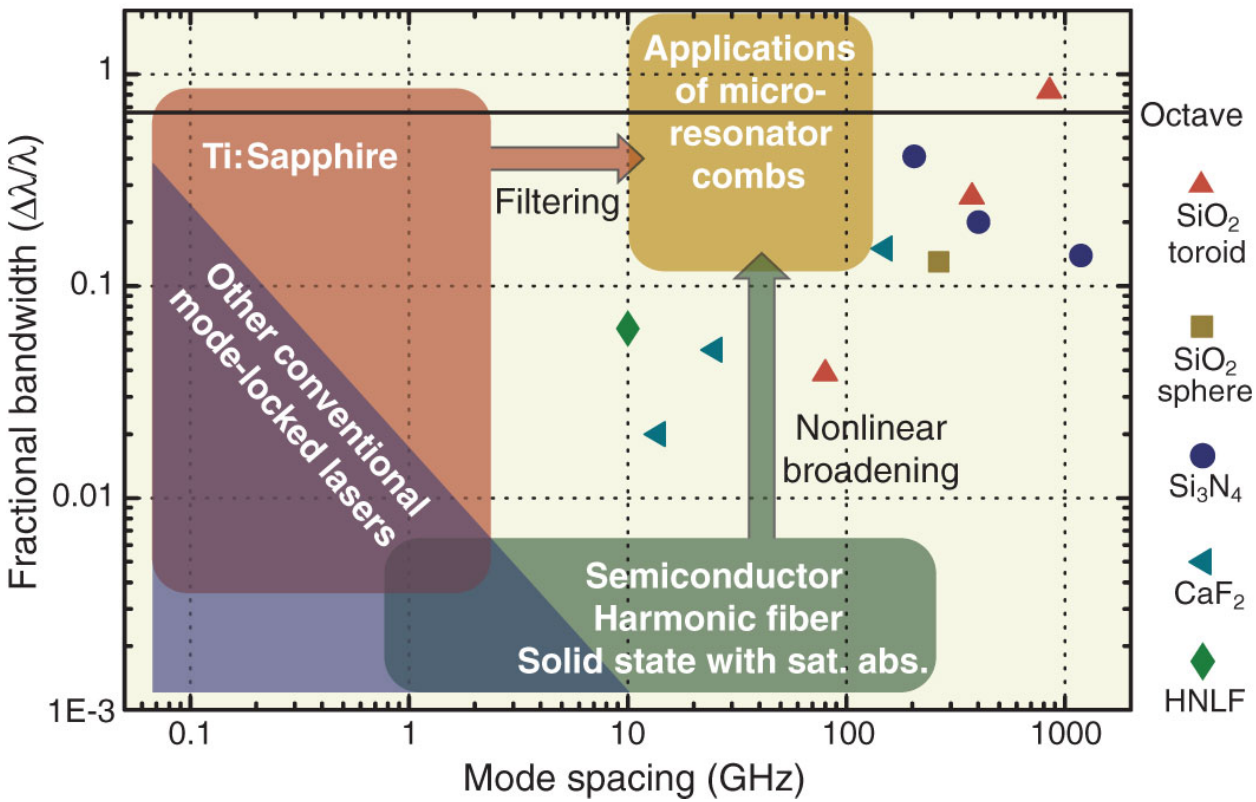




Source: Del'Haye, Phys. Rev. Lett. 107, 063901 (2011), Okawachi, Opt. Lett. 36, 3398 (2011)

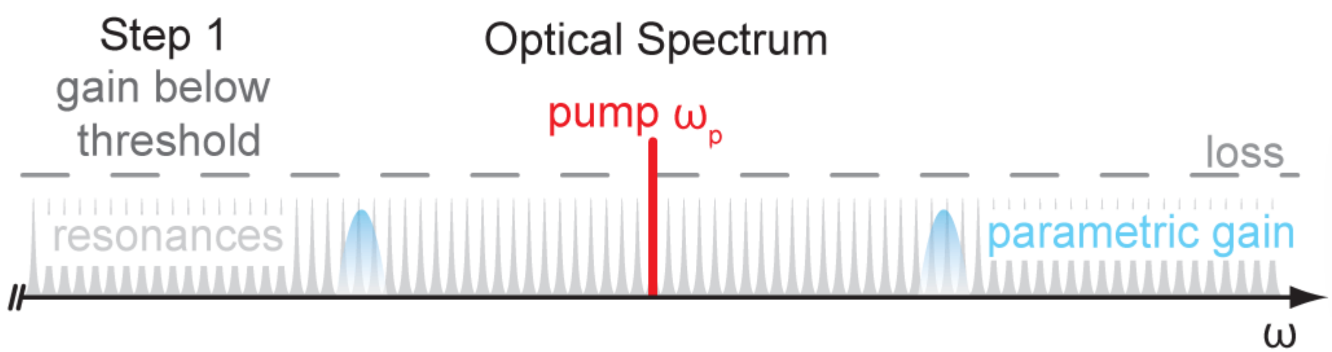
Why microresonators?





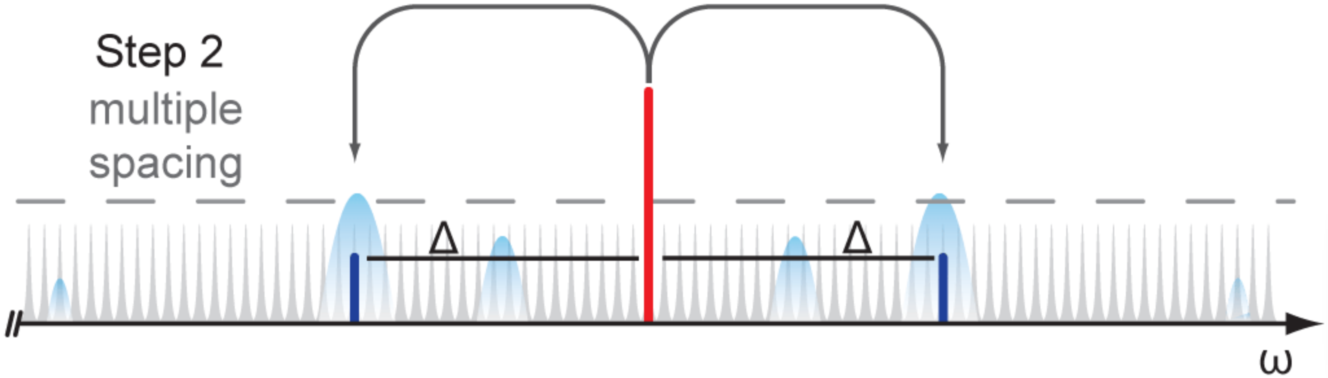
Source: Kippenberg et al., Science (2011)

Comb generation dynamics



Graphics adapted from Herr, arXiv:1111.3071v1, 2011

Comb generation dynamics



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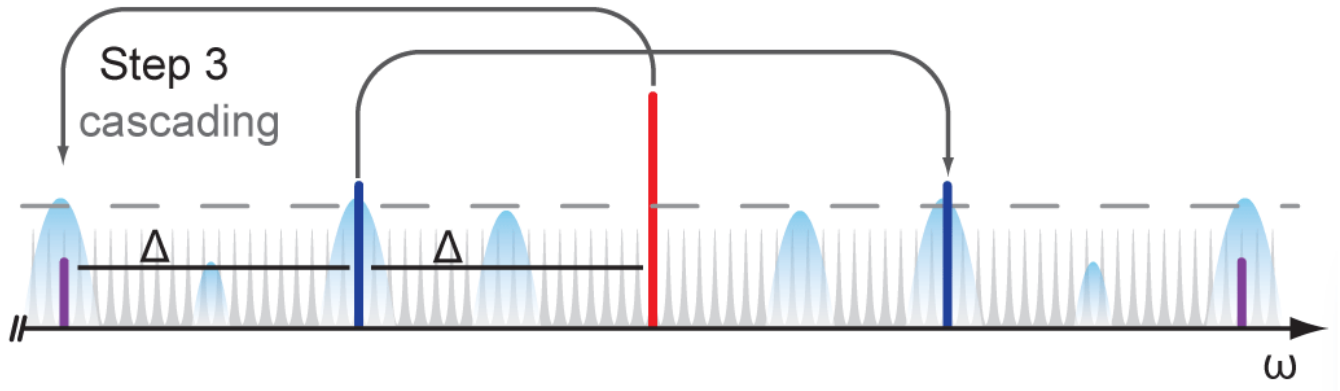
Comb generation dynamics



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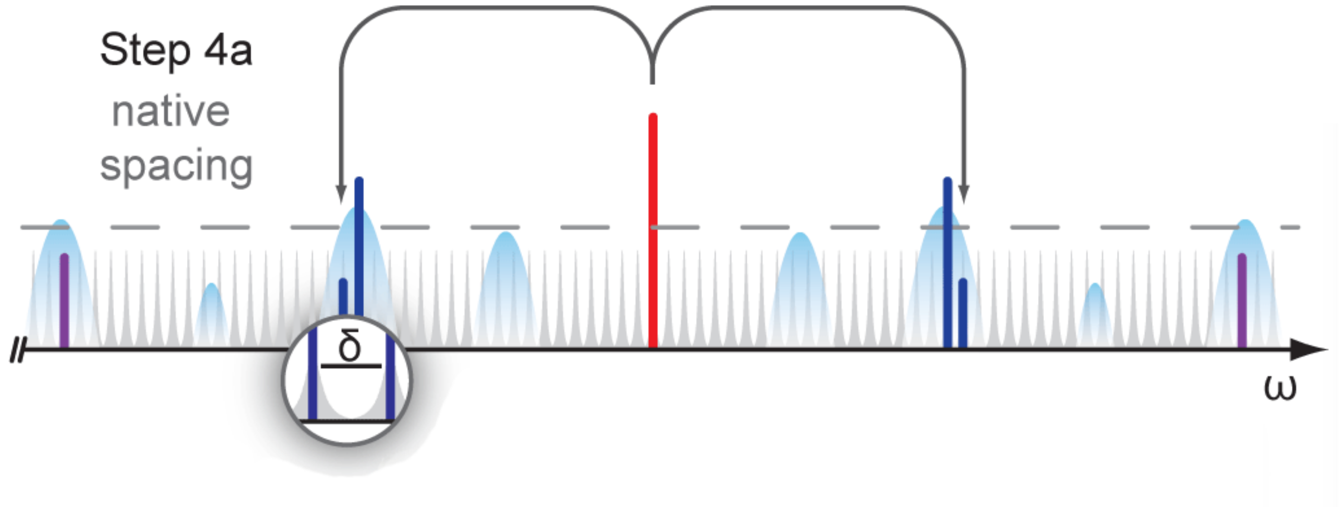
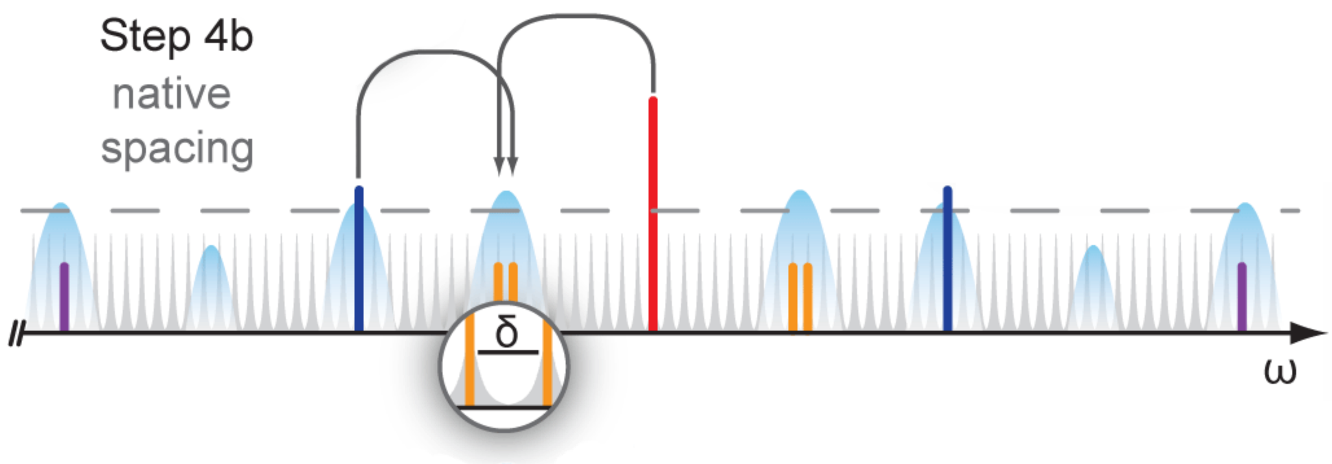


Comb generation dynamics



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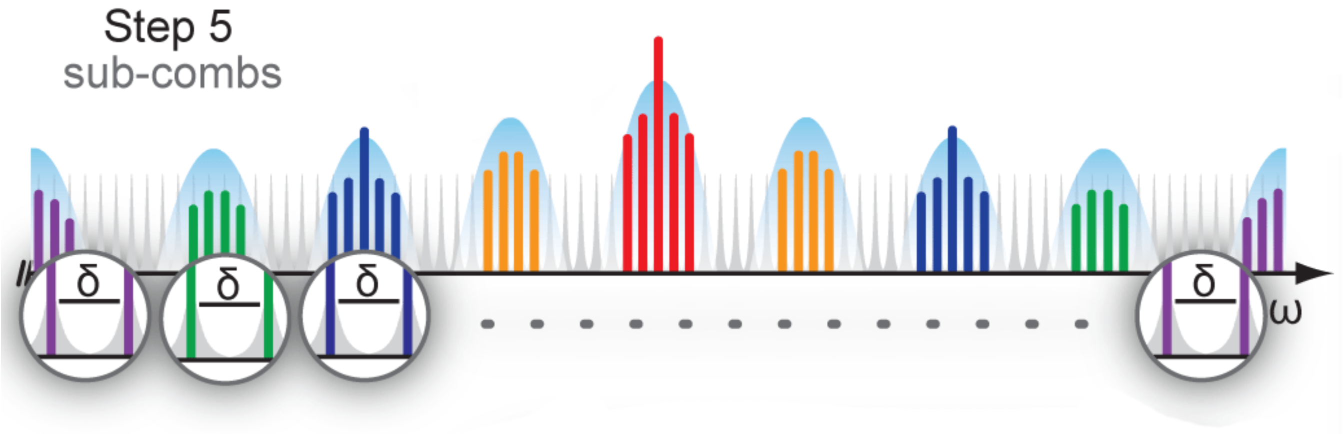
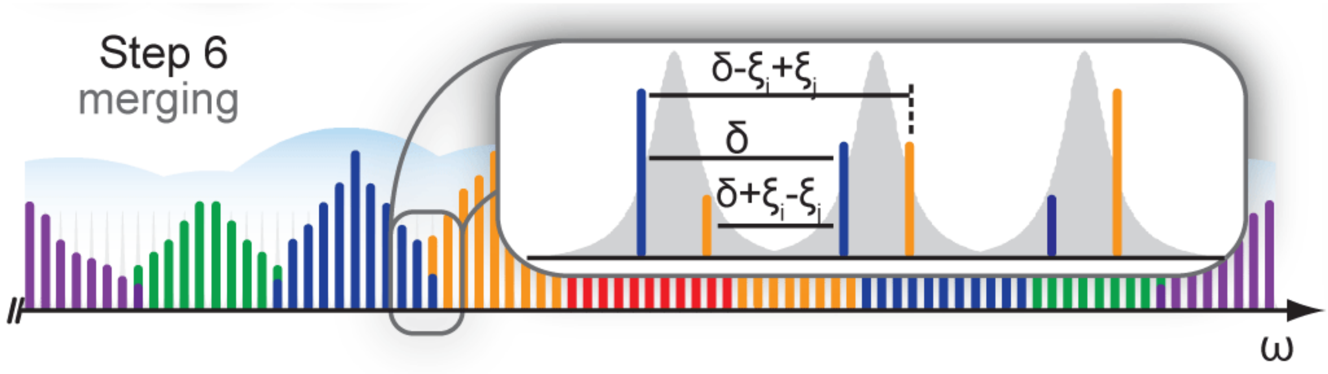
Comb generation dynamics



Graphics adapted from Herr, arXiv:1111.3071v1, 2011

Comb generation dynamics



Graphics adapted from Herr, arXiv:1111.3071v1, 2011

(FY12 BRI) Microresonator-based optical frequency combs


S. Diddams
NIST


Q. Lin
University of Rochester

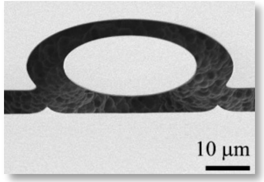

A. Gaeta
Cornell

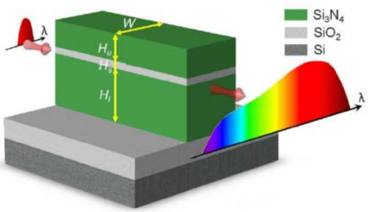

A. Matsko
OEwaves


A. Weiner
Purdue University


A. Willner
USC Optical Communications Laboratory

- **Initiative aimed at exploring the fundamental physics of microresonator comb generation.**
- **Six efforts exploring:**
  - **Spatio-temporal field mapping and control**
  - **Silicon-carbide microdisks**
  - **Silicon nitride resonators**
  - **Mid-IR microresonators**
  - **Time domain characterization**
  - **Dispersion tailoring via slotted waveguides**

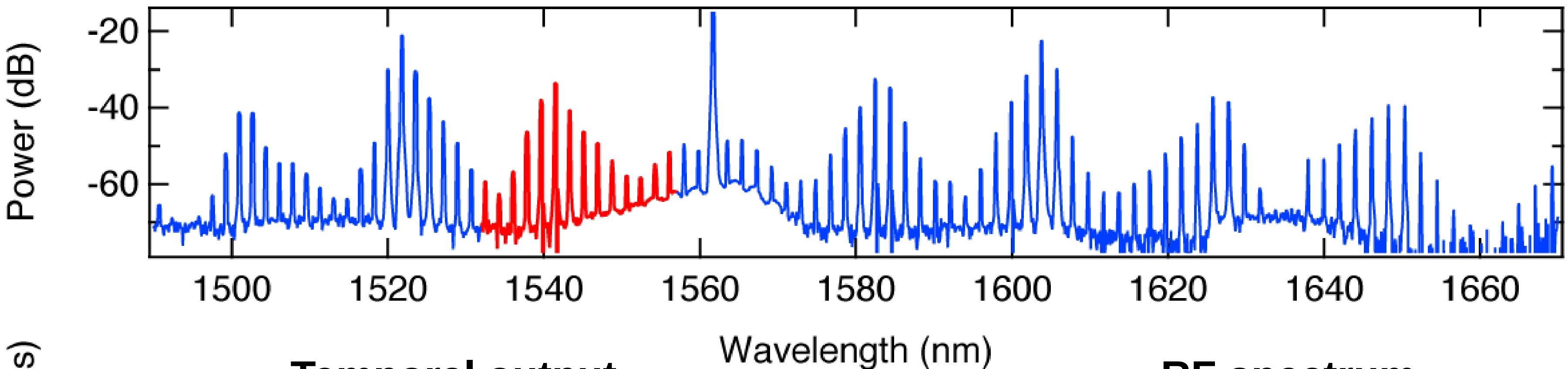




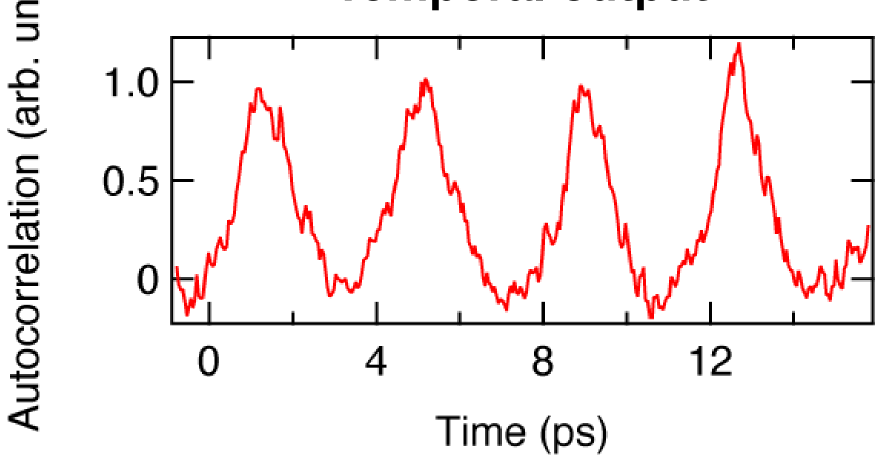
Temporal and Spectral Comb Generation Dynamics

PI: Alex Gaeta, Cornell

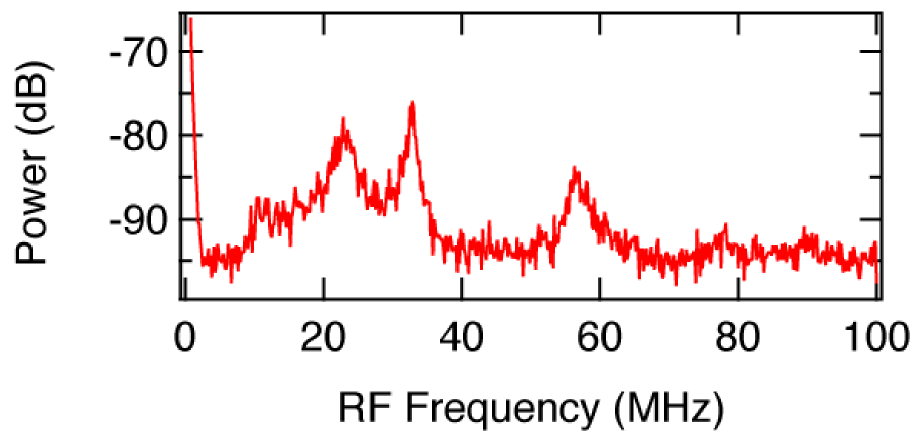
Optical spectrum



Temporal output



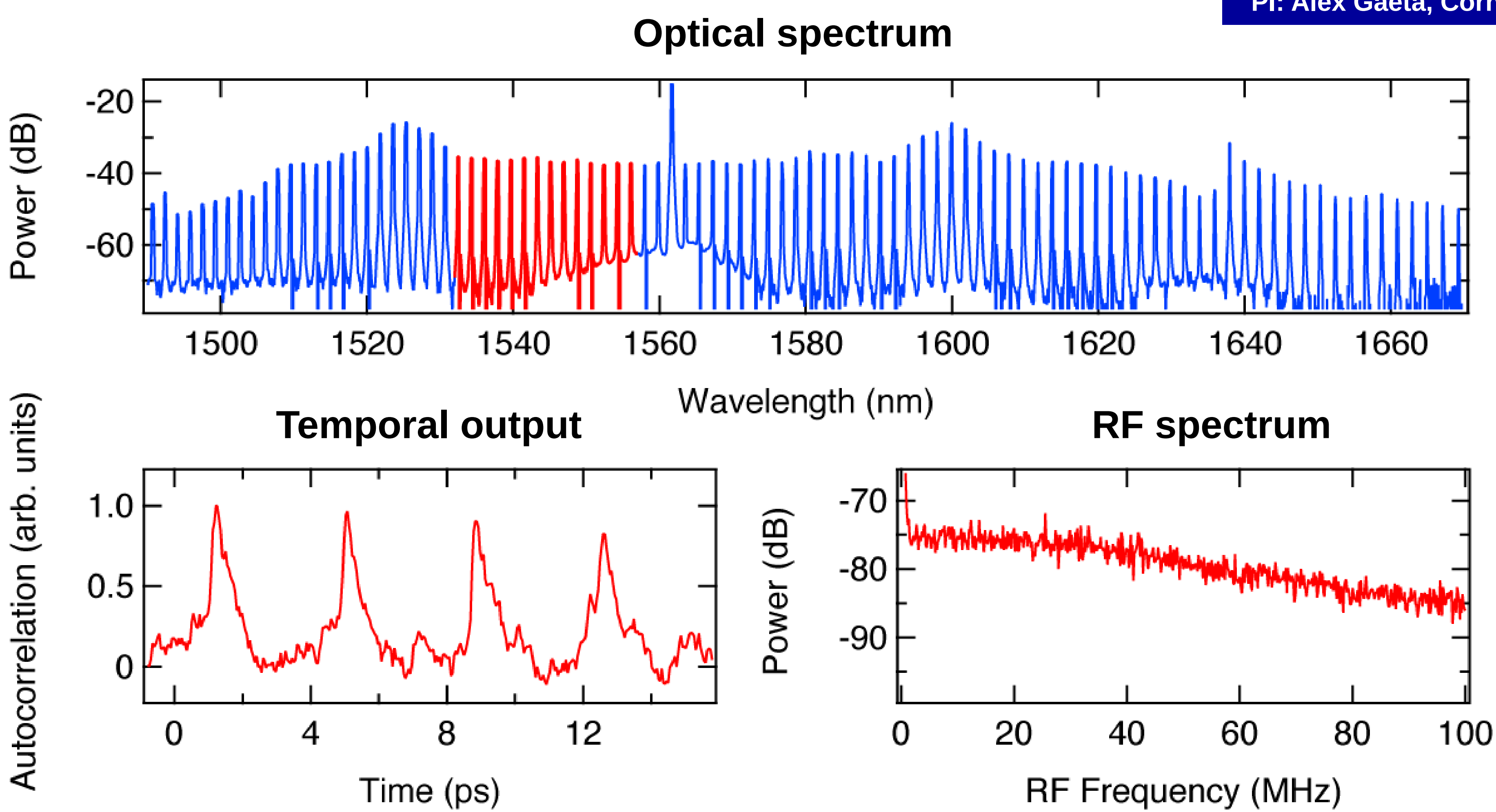
RF spectrum



Source: http://arxiv.org/abs/1211.1096v3

Temporal and Spectral Comb Generation Dynamics

PI: Alex Gaeta, Cornell



Source: http://arxiv.org/abs/1211.1096v3

Temporal and Spectral Comb Generation Dynamics

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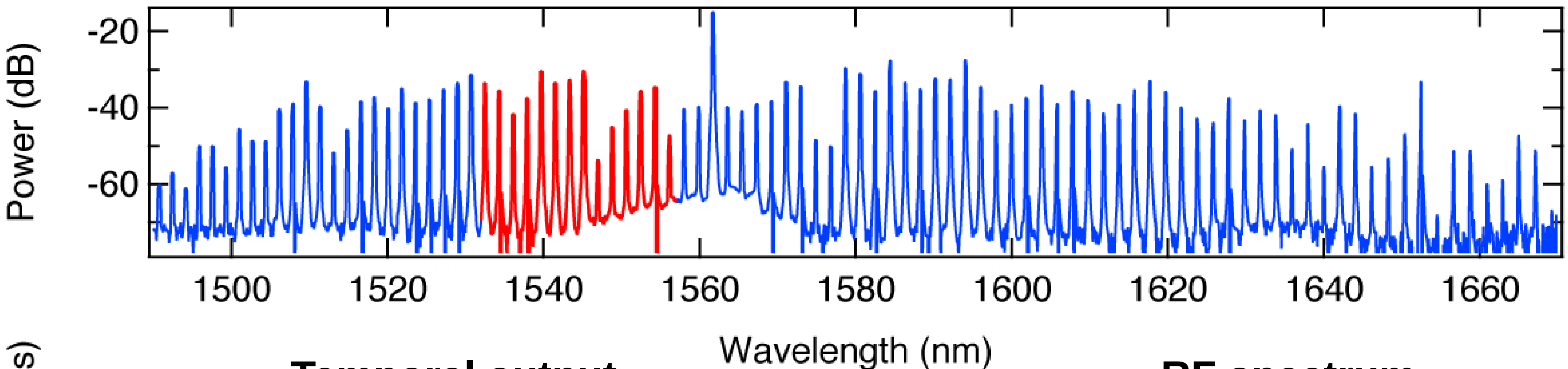
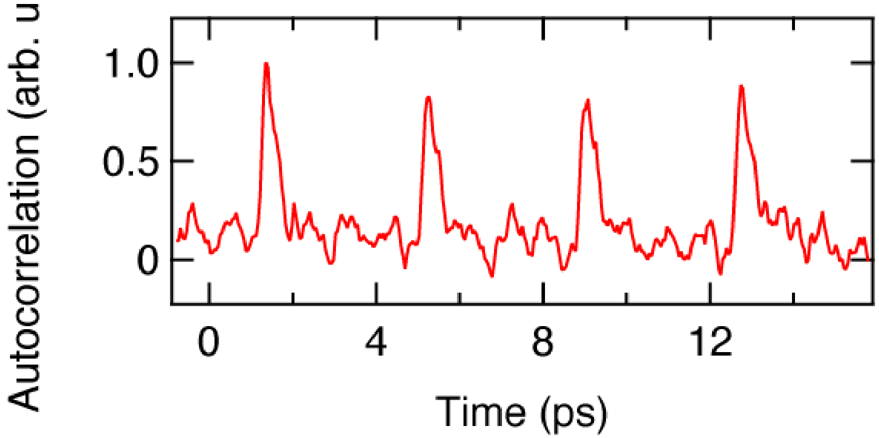
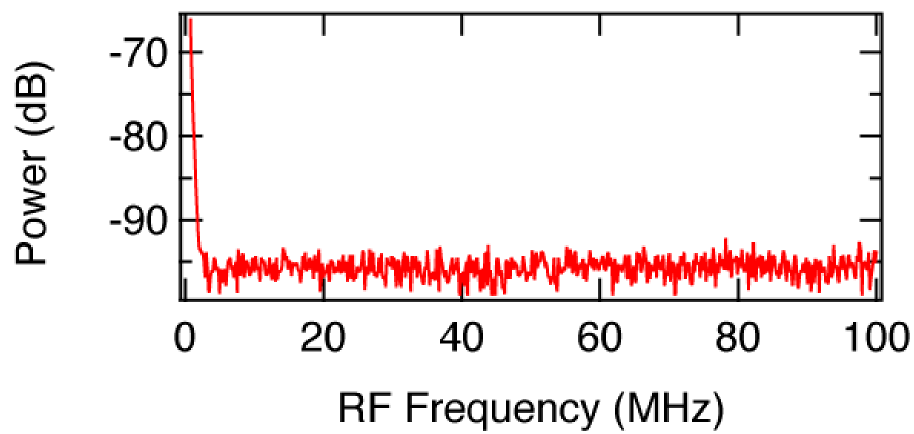
Optical spectrum



Temporal output



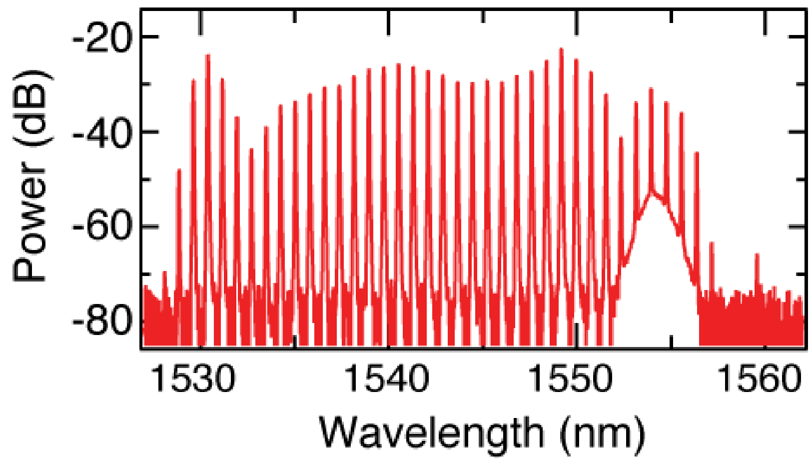
RF spectrum

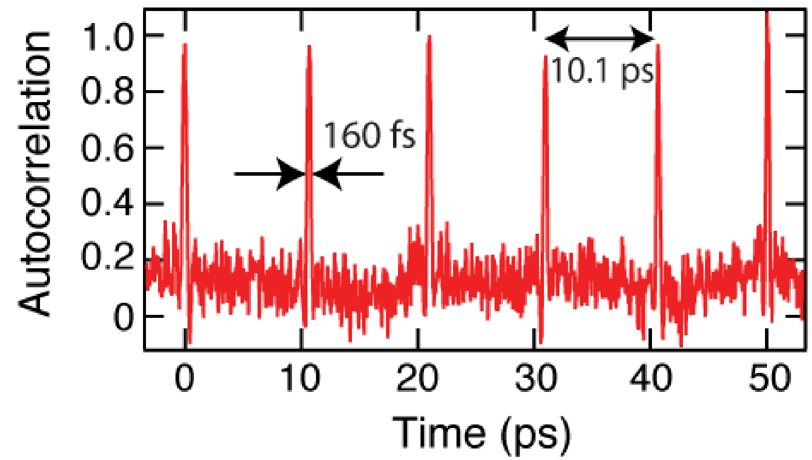


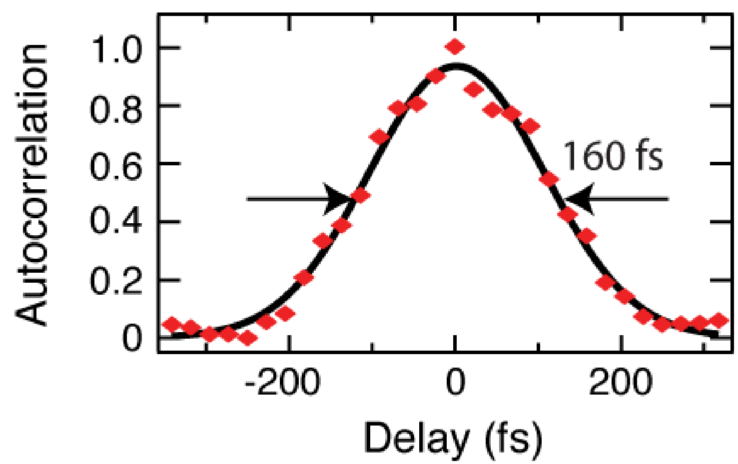
<u>Transition to modelocking?</u>

Ultrashort Pulses at 99 GHz

PI: Alex Gaeta, Cornell







- 99-GHz repetition rate
- 160-fs pulses

Source: http://arxiv.org/abs/1211.1096v3

Outline

– Microresonator-based optical frequency combs

– **High peak power, ultrashort pulse laser processing of materials**

– Extreme ultraviolet (EUV) comb spectroscopy

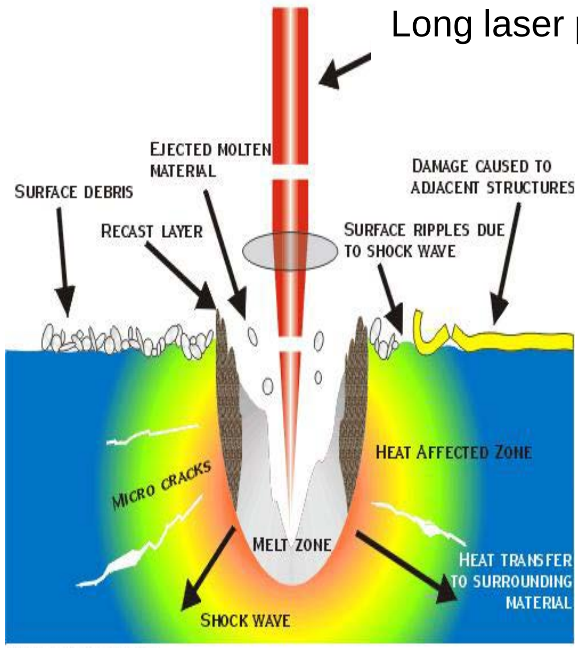
– High harmonic interferometry

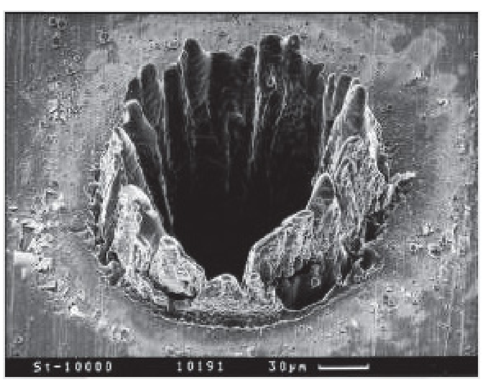
– Relativistic optics

Photo credits: DOI: 10.1038/nature05524, www.attoworld.de, E. Chowdhury (OSU)

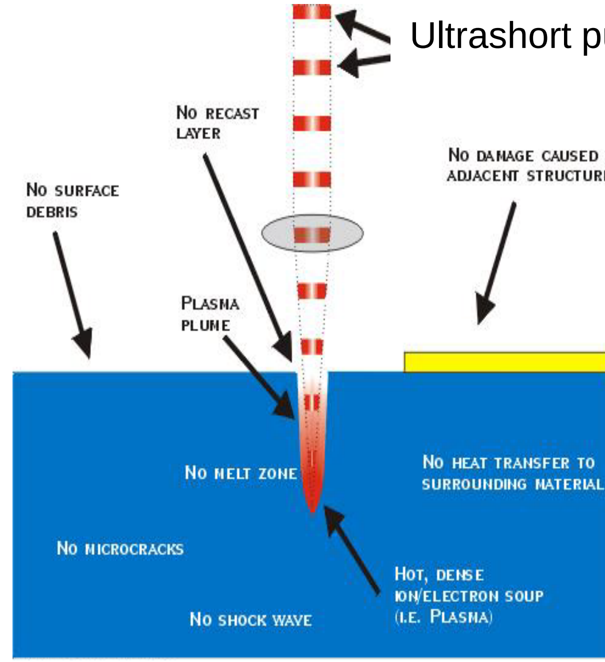
Long laser pulse damages adjacent structures Ultrashort pulses → no collateral damage

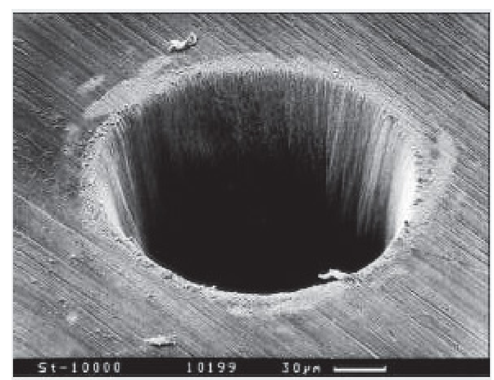
Long laser pulse





Ultrashort pulses

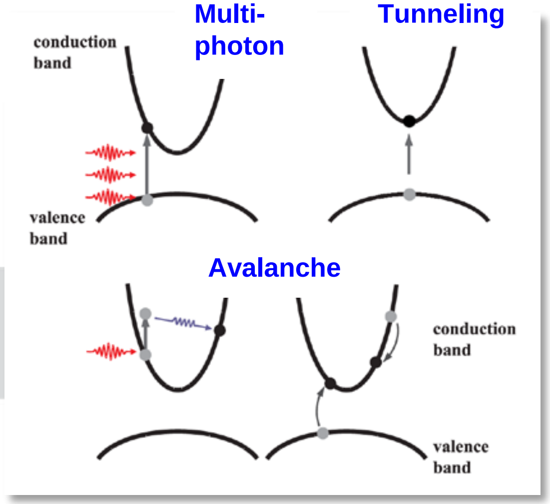




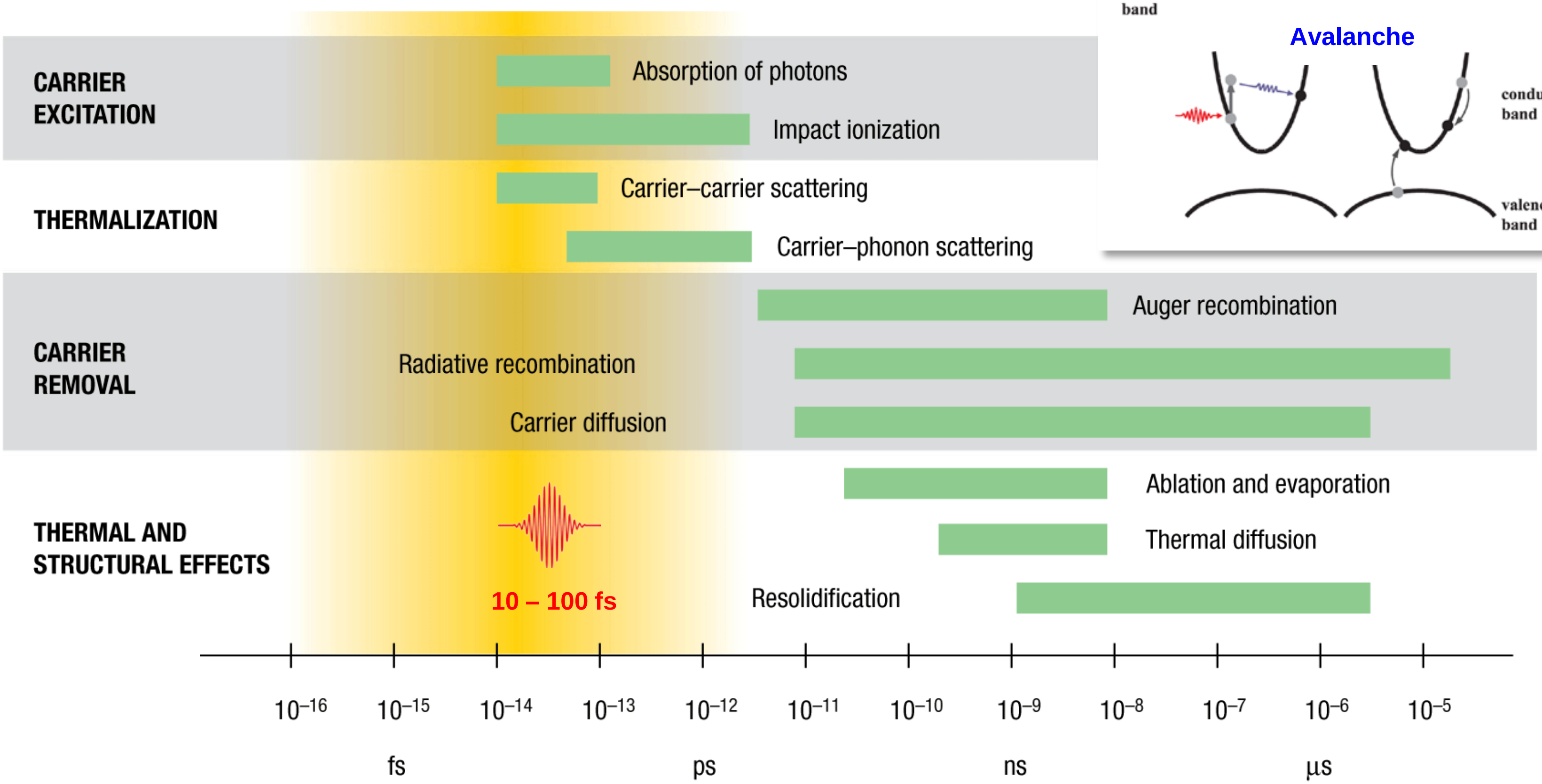
Source: C. Momma, A. Tunnermann et al., Opt. Commun. 129, 134 (1996)

Time-dependent processes in materials

Excitation mechanisms



Timescales of electron and lattice processes in laser-excited solids

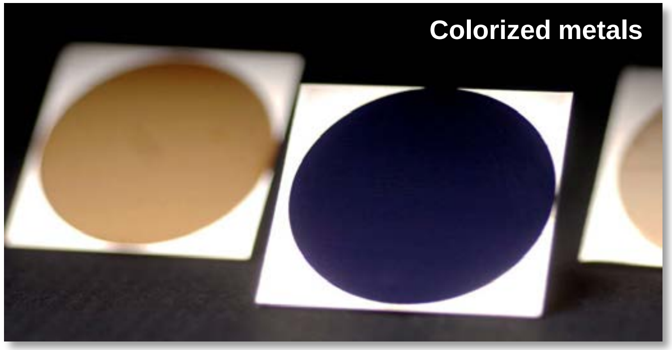


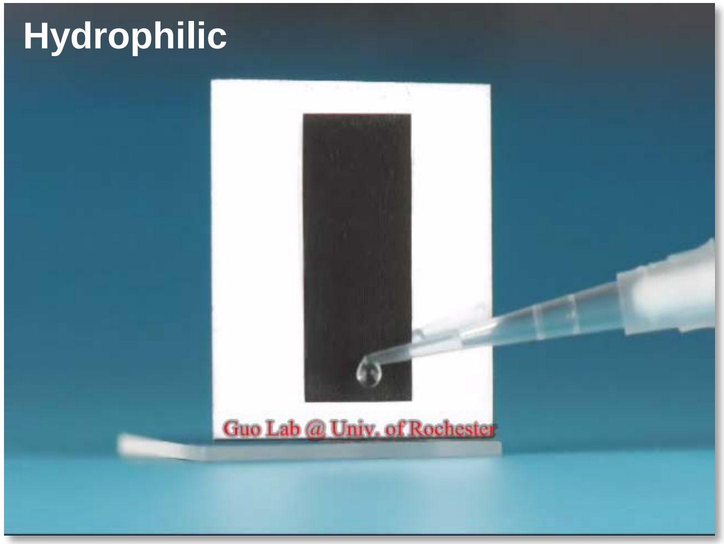
Source: Sundaram, Nat Mater 1, 217 (2002), Mao, Applied Physics A 79, 1695 (2004).

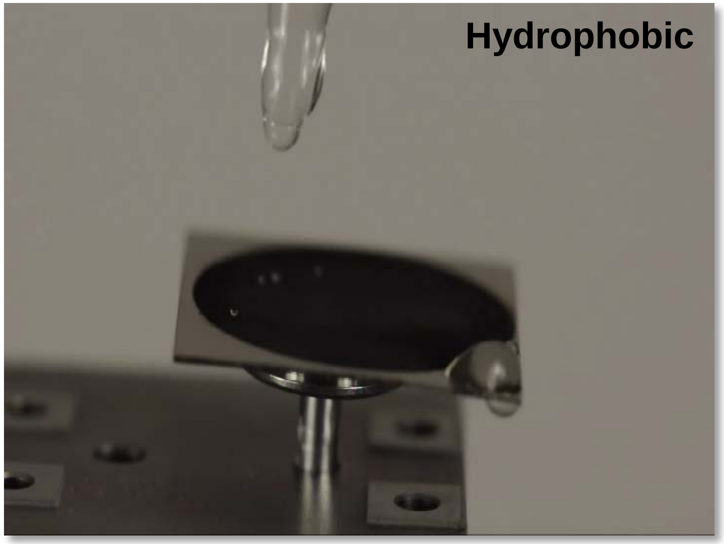
High peak power, ultrashort pulse laser processing of materials

PI: Chunlei Guo, U of Rochester

- Ultrashort laser pulses open up novel possibilities and mechanisms for laser-solid interactions.
- Demonstrated femtosecond laser processing and surface texturing techniques to engineer surface structures & properties (e.g. darkened & colorized metals, hydrophilic & hydrophobic surfaces).







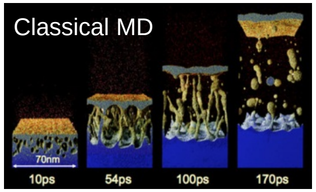
(FY13 BRI) High peak power, ultrashort pulse laser processing of materials

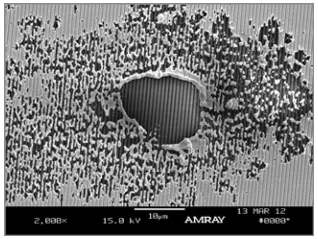
S. Yalisove
Michigan Engineering

P. Polynkin
The University of Arizona

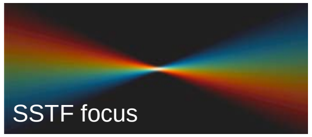
Chowdhury
Ohio State

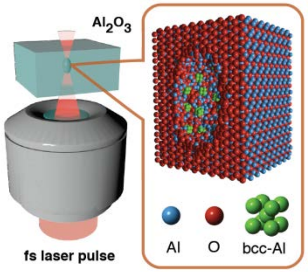
- **Initiative aimed at developing a fundamental understanding of intense field laser ablation/damage in the femtosecond regime.**
- **Three multi-PI efforts exploring:**
  - **Dynamics of ionization**
  - **Fundamental dynamics of laser ablation**
  - **Defect states in multi-pulse interaction**
  - **Effect of structures on laser damage**
  - **First principle-based models, non-adiabatic quantum MD, classical MD**
  - **Vary λ = 400 nm – 4 µm, τ = 5 – 1000 fs**
  - **Complex beam shapes (Bessel, Airy, vortex, SSTF beams)**
  - **Novel laser-matter interaction geometries (confined microexplosions, SSTF excitation, few-cycle pulses)**





Gratings





AFRL

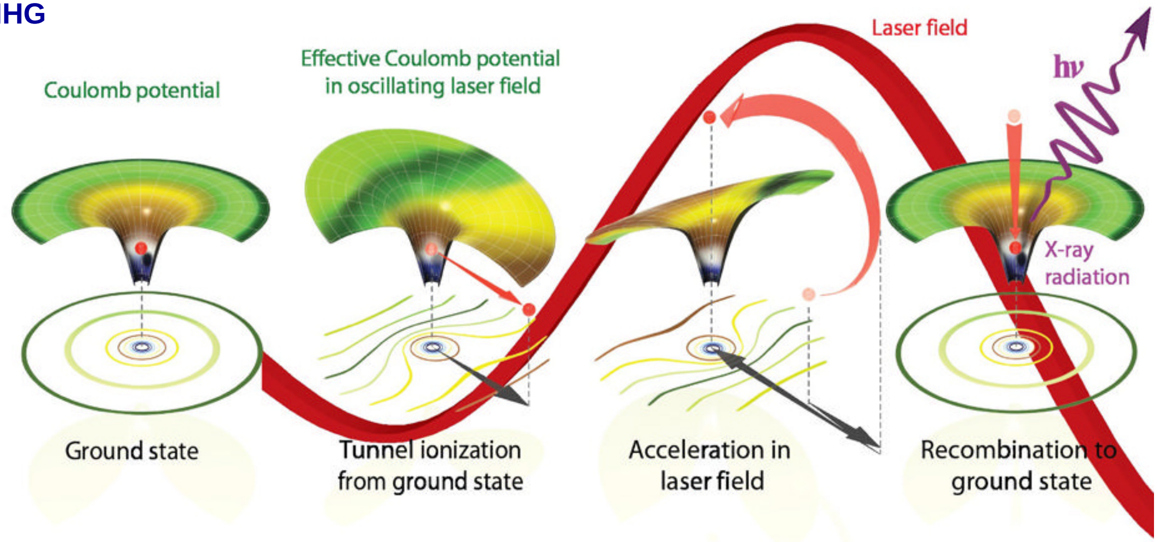
Outline

- – Microresonator-based optical frequency combs
- – High peak power, ultrashort pulse laser processing of materials
- – **Extreme ultraviolet (EUV) comb spectroscopy**
- – High harmonic interferometry
- – Relativistic optics

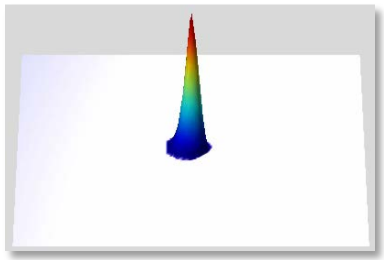
Photo credits: DOI: 10.1038/nature05524, www.attoworld.de, E. Chowdhury (OSU)

High Harmonic Generation (HHG)

Microscopic single-atom physics of HHG

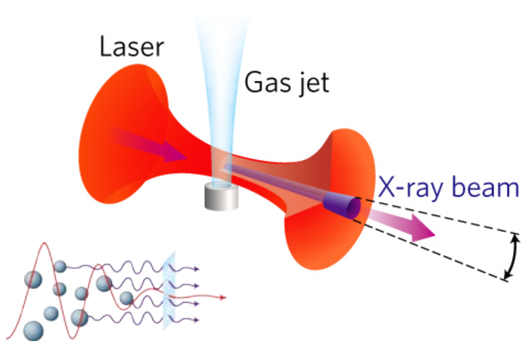


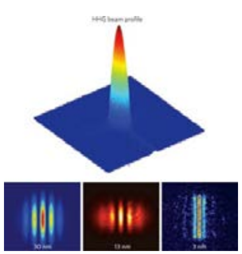
2D electron wavepacket quantum simulation

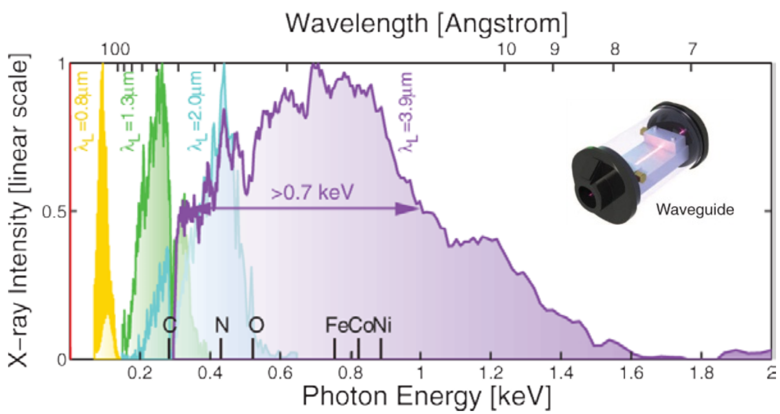


Source: Luis Plaja, U Salamanca

Macroscopic phase-matched harmonic emission



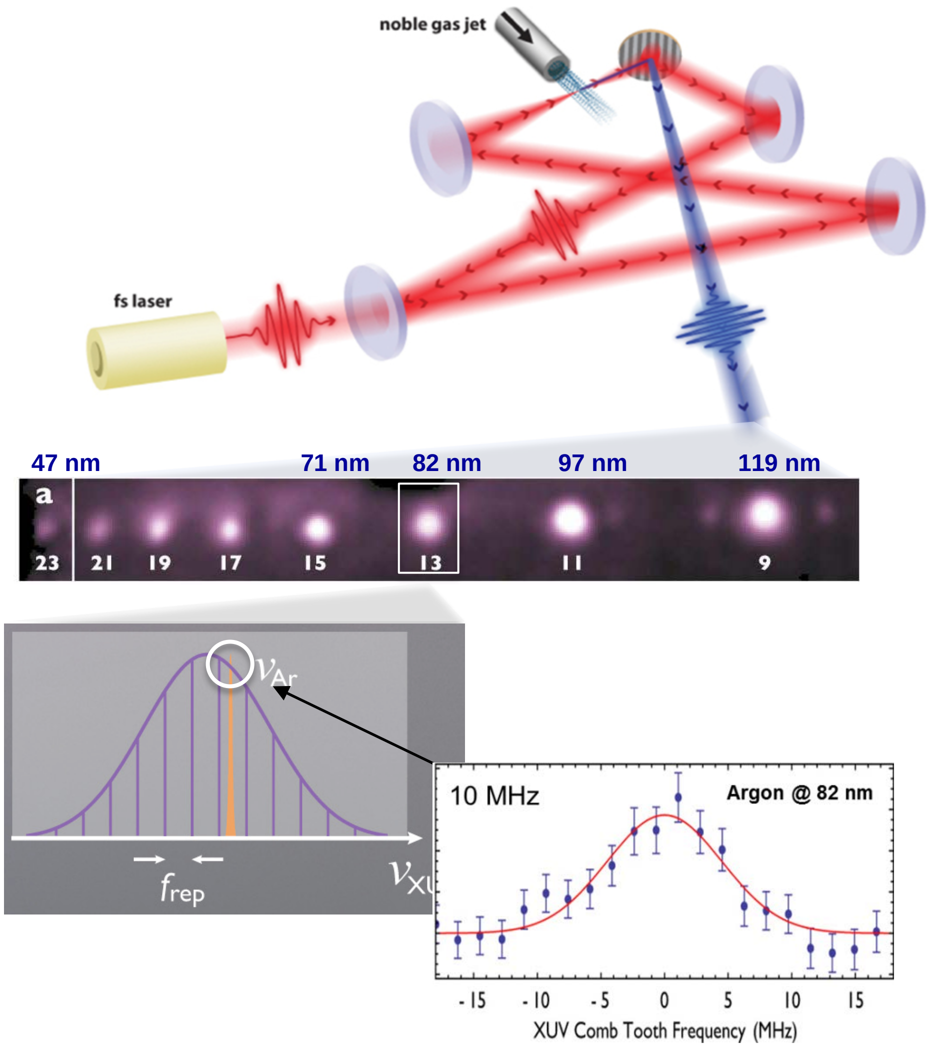




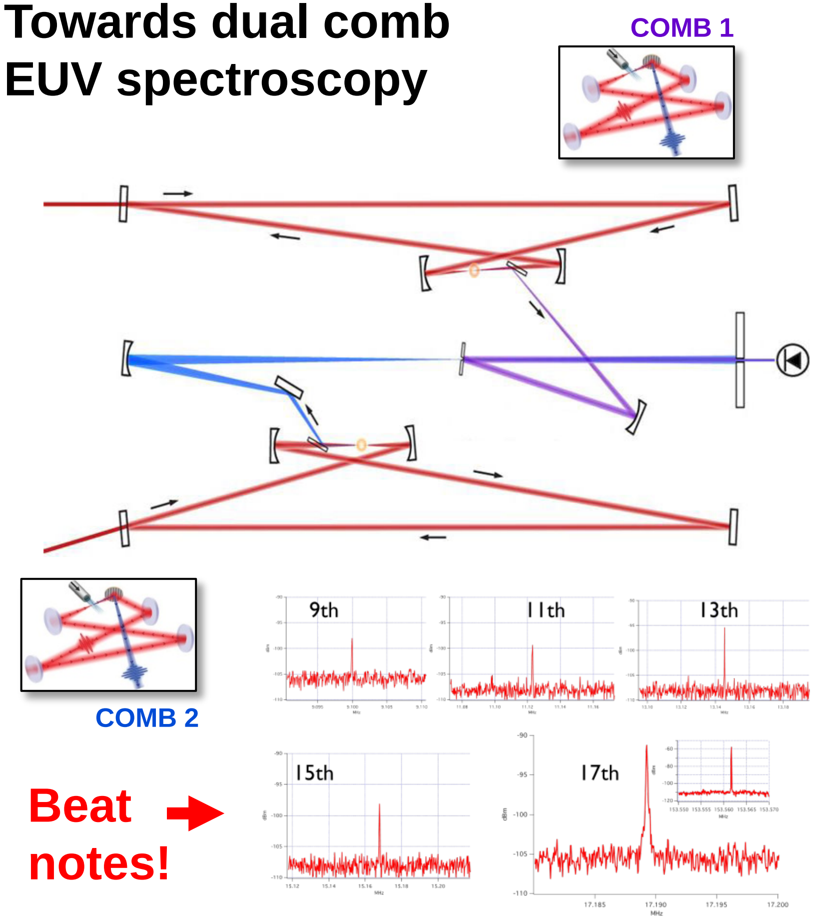
Source: Popmintchev, Nat Photonics 4, 822 (2010), Popmintchev, Science 336, 1287 (2012)

Direct Frequency Comb Spectroscopy in the Extreme Ultraviolet

PI: Jun Ye, U of Colorado



Towards dual comb EUV spectroscopy



Unpublished

Source: Cingoz, Nature 482, 68 (2012)

Outline

FREQ – Microresonator-based optical frequency combs

TIME – High peak power, ultrashort pulse laser processing of materials

FREQ – Extreme ultraviolet (EUV) comb spectroscopy

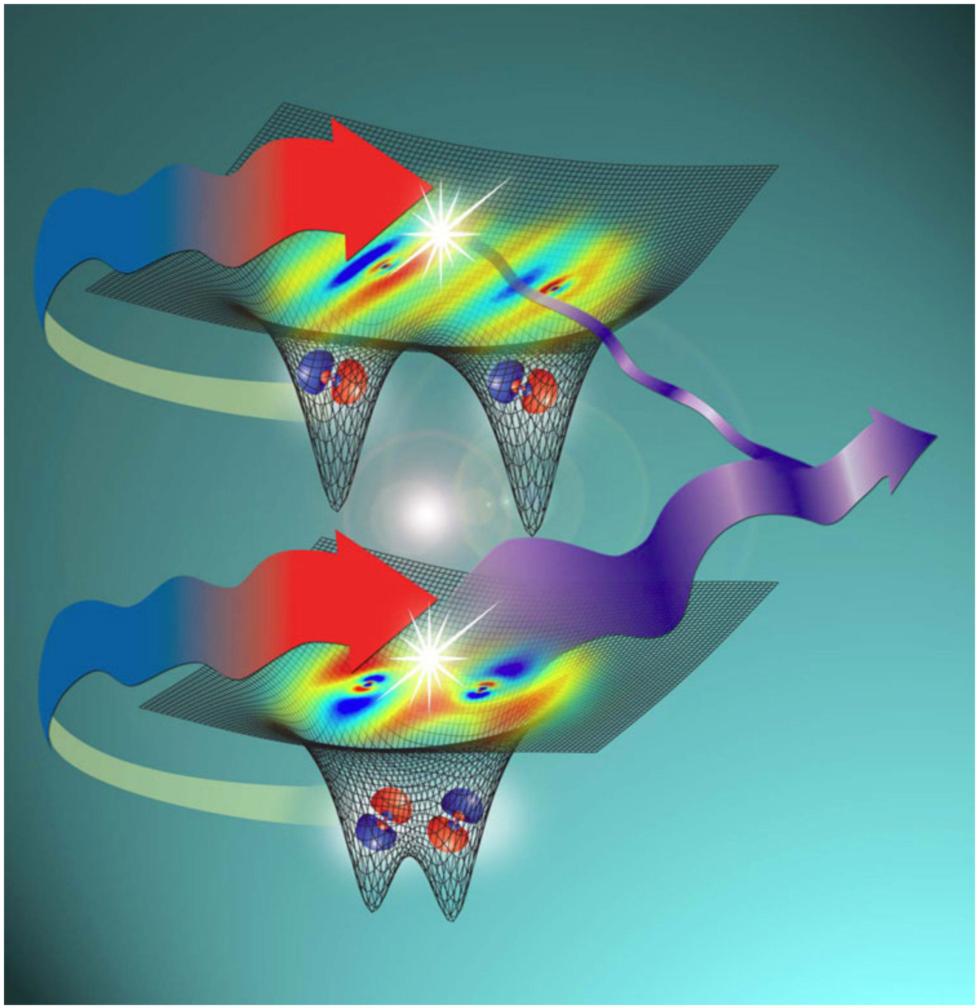
TIME – **High harmonic interferometry**

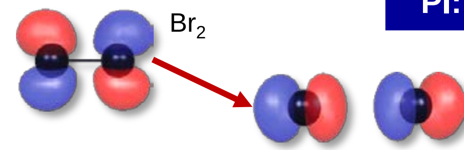
PEAK – Relativistic optics

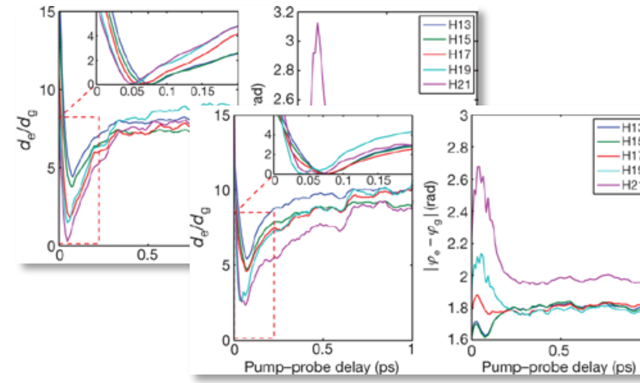
Photo credits: DOI: 10.1038/nature05524, www.attoworld.de, E. Chowdhury (OSU)

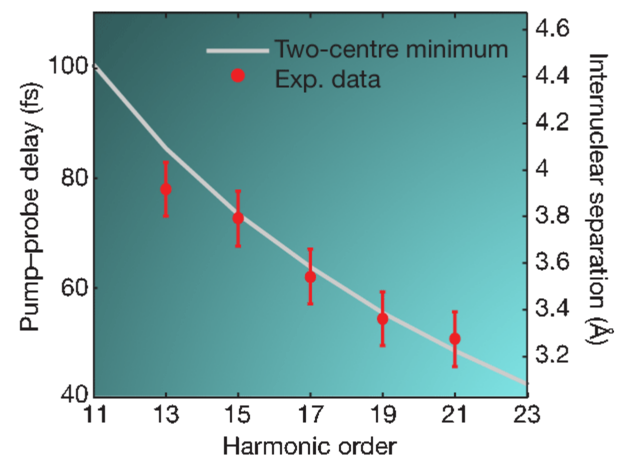
High Harmonic Interferometry to follow chemical reactions

PI: Paul Corkum, NRC





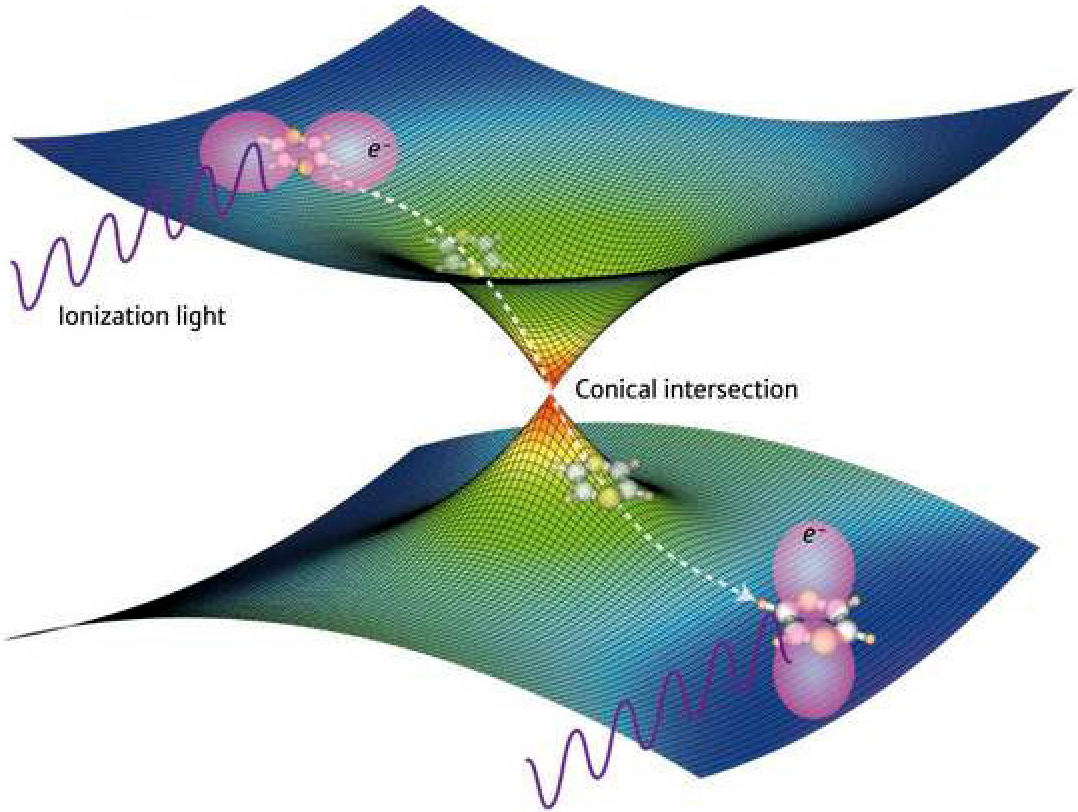




Source: Worner, Nature 466, 604 (2010).

Conical intersections drive the chemistry of complex molecules

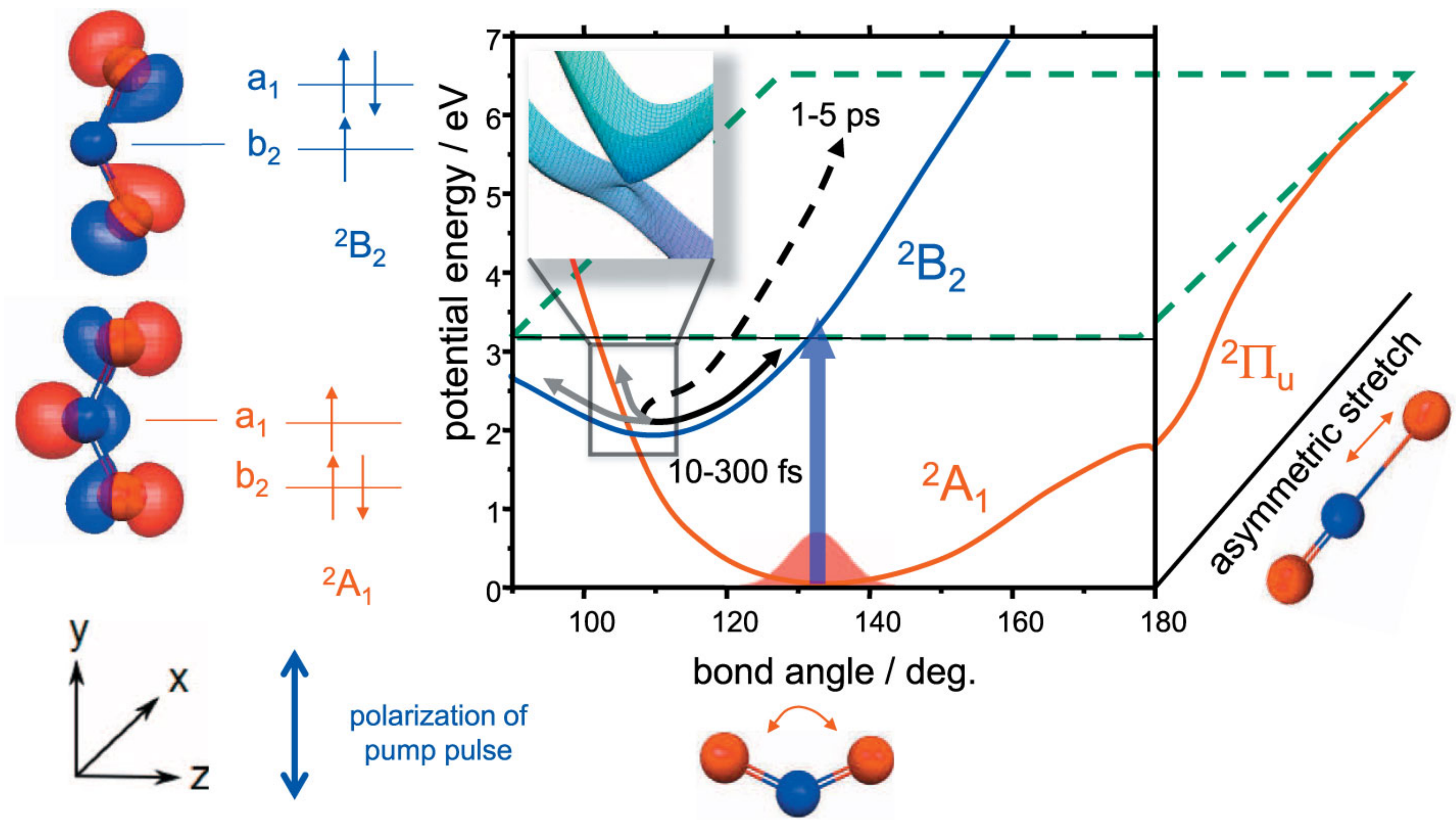
PI: Paul Corkum, NRC



Source: Paul Corkum

Conical Intersection Dynamics in NO_2

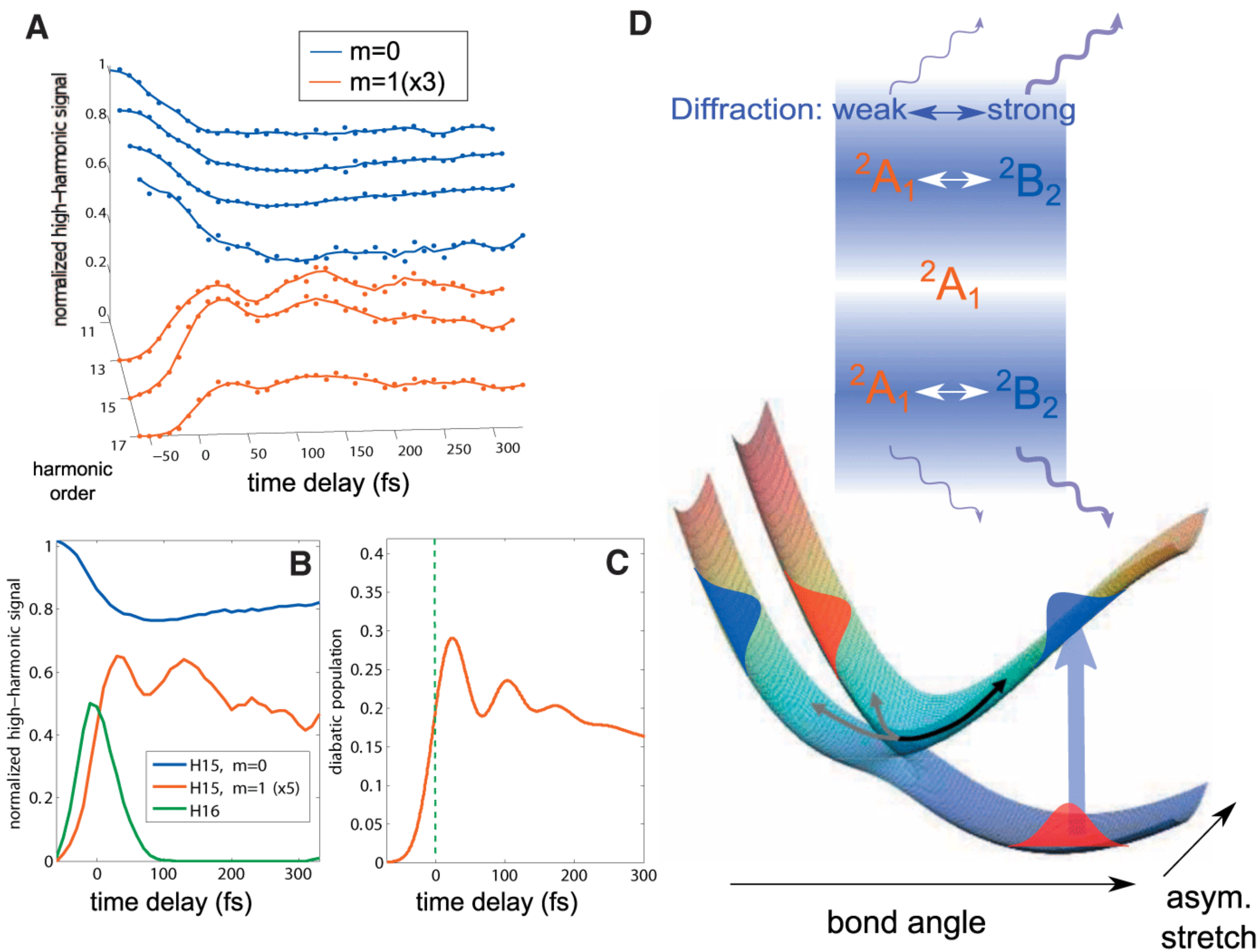
PI: Paul Corkum, NRC



Source: Wörner, Science 334, 208 (2011)

Electronic dynamics near a conical intersection

PI: Paul Corkum, NRC



Source: Wörner, Science 334, 208 (2011)

Outline

FREQ – Microresonator-based optical frequency combs

TIME – High peak power, ultrashort pulse laser processing of materials

FREQ – Extreme ultraviolet (EUV) comb spectroscopy

TIME – High harmonic interferometry

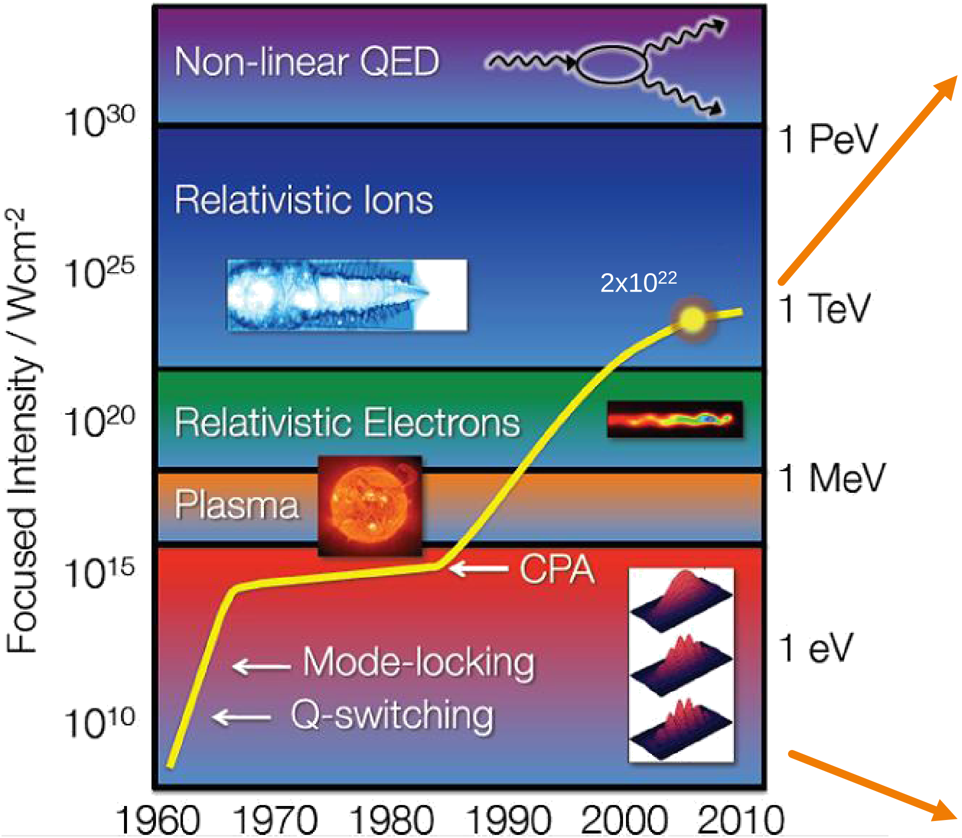
PEAK – **Relativistic optics**

Photo credits: DOI: 10.1038/nature05524, www.attoworld.de, E. Chowdhury (OSU)

Progress in peak intensity

- **Over the last two decades, a 6 order of magnitude increase in achieved focused intensities in table-top systems.**

Source: CUOS website



Relativistic ions
Nonlinearity of vacuum

GeV e acceleration
e+e- production
Nuclear reactions

Relativistic plasmas
Hard x-ray generation

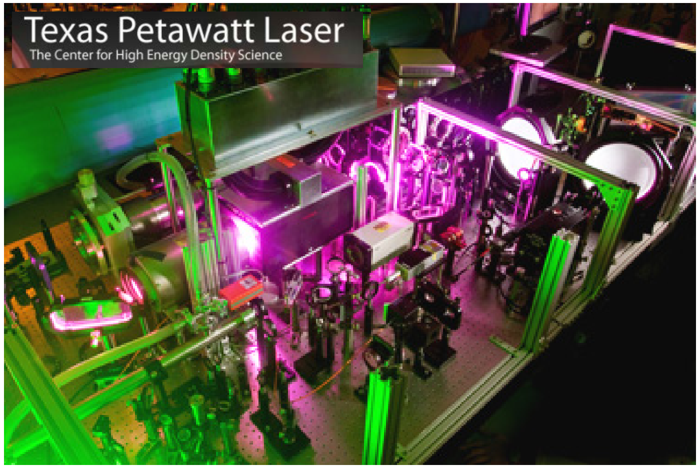
Tunnel ionization
High temperature plasma formation
Bright x-ray generation

Nonperturbative atomic physics
High order nonlinear optics

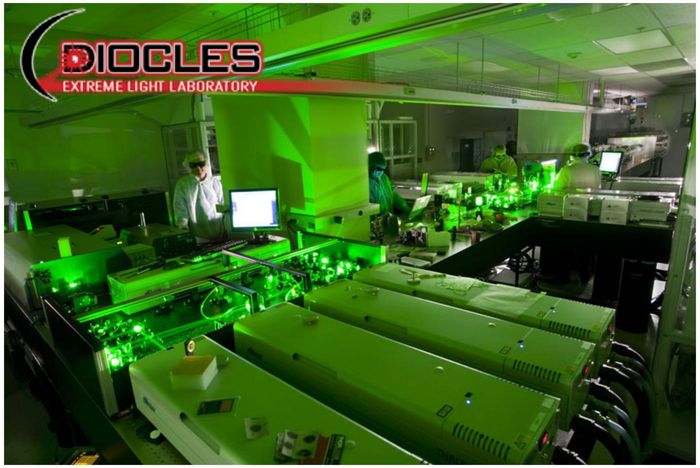
Perturbative atomic physics
Nonlinear Optics

Petawatt class university lasers

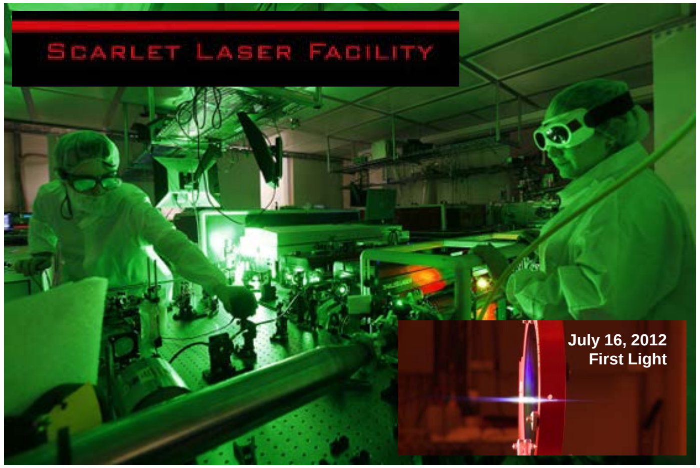
University of Texas, 1.1 PW



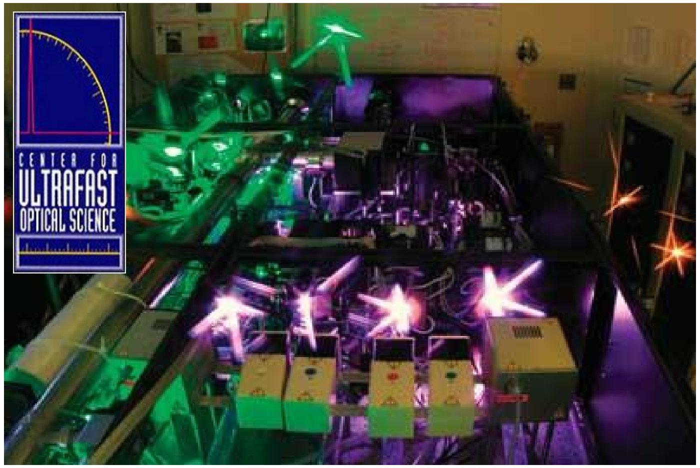
University of Nebraska, 0.7 PW



Ohio State University, 0.5 PW



University of Michigan, 0.3 PW

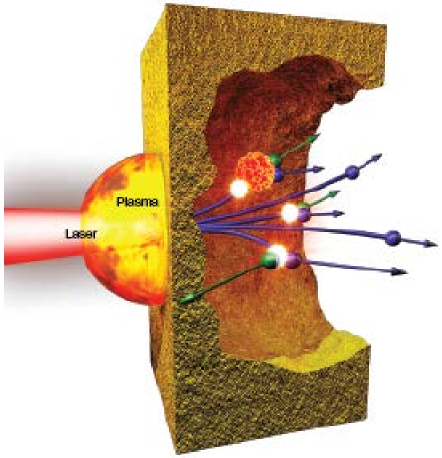


Laser-driven x-ray sources

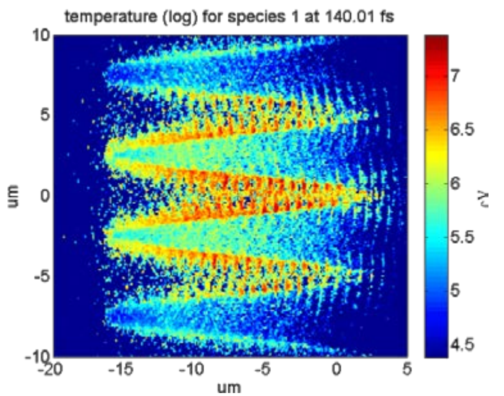
PI: Kramer Akli, OSU

- **Understanding laser-generated electron beam characteristics is the key to advancing x-ray sources.**
- **PIC simulations of high intensity short pulse laser interacting with structured targets yields an enhancement in the number and energy of hot electron.**
- **Monte Carlo simulations using the electron beam source from PIC show enhancement of x-ray production.**

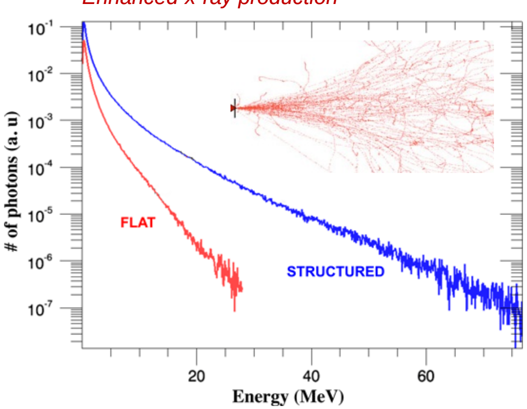
Picture: Courtesy of Kwei--Yu Chu and Lawrence Livermore National Laboratory



Hot electron generation



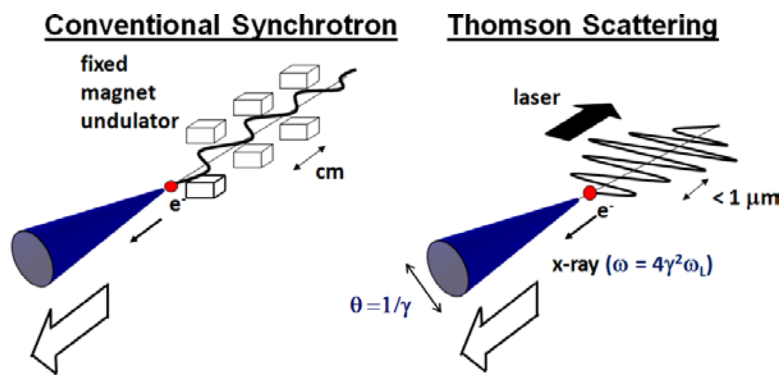
Enhanced x-ray production

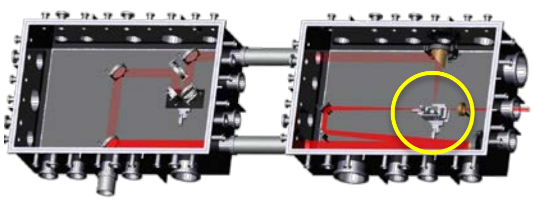


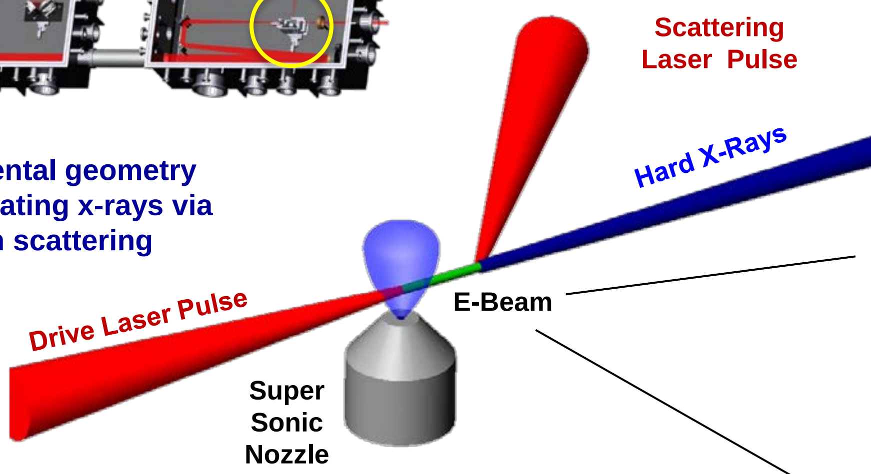
Laser-driven x-rays generation (0.1 – 10 MeV)

PI: Donald Umstadter, U of Nebraska

- **Scattering from a 300 MeV electron beam can Doppler shift a 1-eV energy laser photon to 1.5 MeV energy.**
- **Demonstrated > 710 MeV electron beams with no detectable low-energy background.**

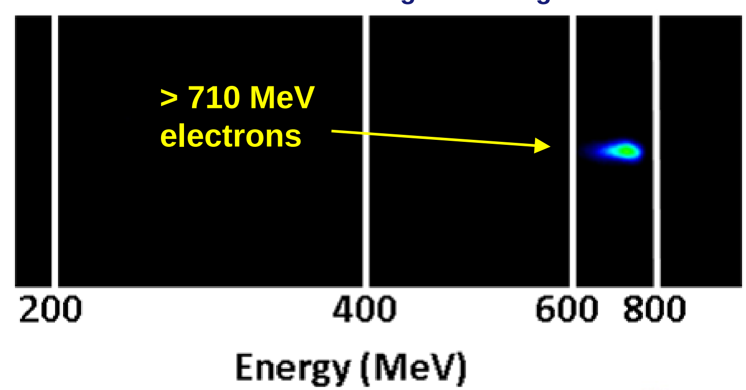






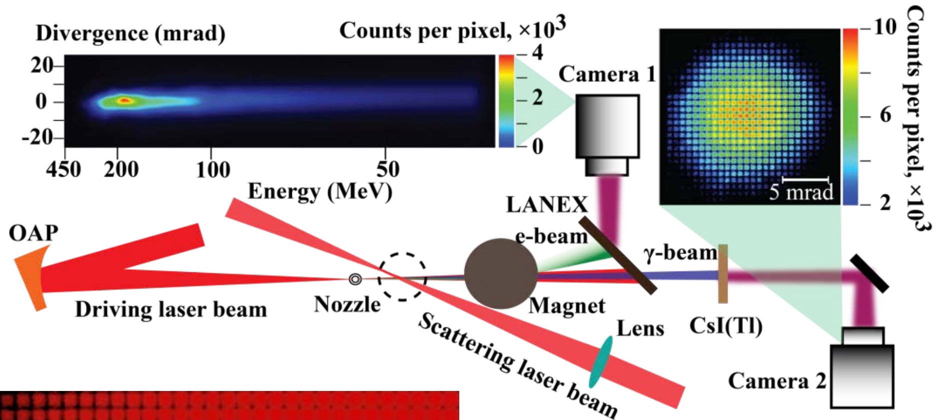
Experimental geometry for generating x-rays via Thomson scattering

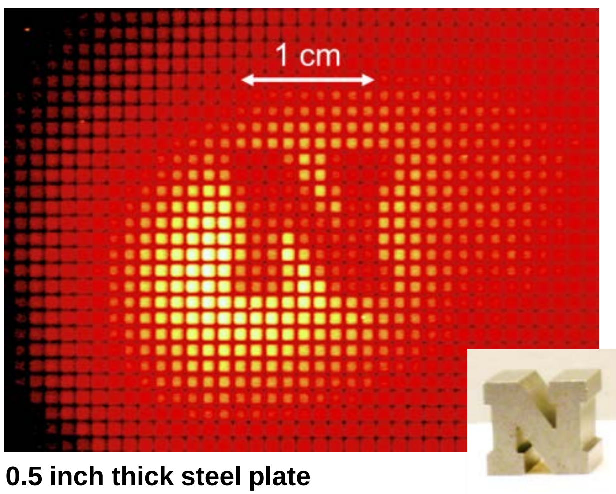
Energy tunability from 0.1 – 0.8 GeV.
Monoenergetic: ΔE/E ~ 10 %
Low angular divergence: 1-5 mrad



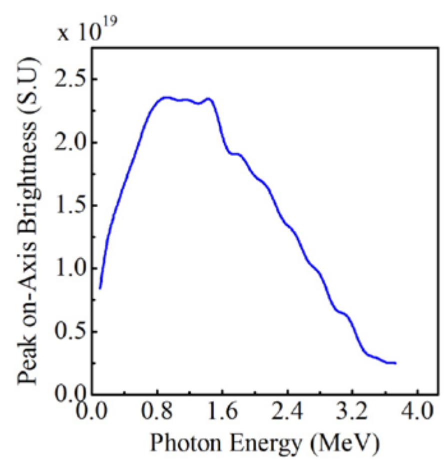
Laser-driven x-rays generation (0.1 – 10 MeV)

PI: Donald Umstadter, U of Nebraska





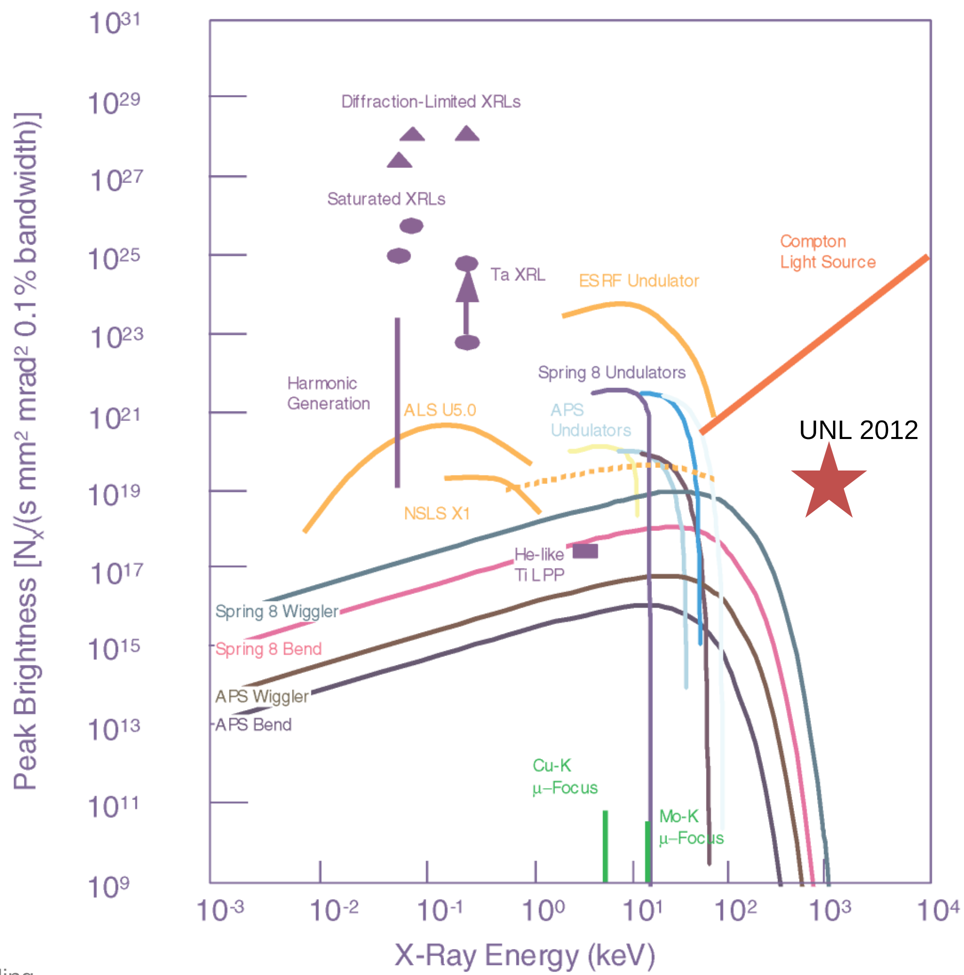
0.5 inch thick steel plate



Beam	Parameter	Sym	Value
ω_0	Energy	E_{laser}	0.5 J/ pulse
	Wavelength	λ	800 nm
	Pulse duration	τ_s	90 fs (FWHM)
	Spotsize	σ_L	9.4 ± 0.4 μm (RMS)
	Number of laser oscillations/pulse	N_{laser}	34
	Average power	P_L	5.6 TW
	Normalized field strength	a_0	0.4
	Photon energy	E_L	1.5 eV
	Interaction angle	Φ	170 deg
e	Source size	σ_e	6.0 ± 2.6 μm (RMS)
	Cutoff energy[i]	E_c	250 MeV
	Divergence[ii]	θ_e	5 mrad (FWHM)
	Total charge	Q	120 pC
γ	Source size	σ_γ	5.1 ± 2.6 μm (RMS)
	Divergence	θ_γ	12.7 mrad (FWHM)
	Peak energy	E_γ	1.2 MeV
	Total photon number/pulse	N_γ	~10^7
	Peak on-axis brilliance	B_x	2.3 x 10^{19} photons/s-mm^2-mrad^2 (0.1% BW)

Brighter, more energetic and tunable than conventional synchrotrons

PI: Donald Umstadter, U of Nebraska



Hartemann, F. V. et al. High-energy scaling of Compton scattering light sources. Physical Review Special Topics - Accelerators and Beams 8, 100702 (2005).

(FY14 BRI) Laser-matter interactions in the relativistic optics regime

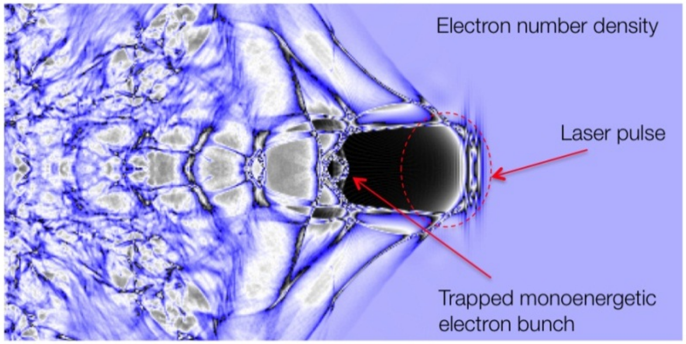
- **Laser-driven electron acceleration**
  - **Laser Wakefield Acceleration: Electrons are accelerated to gigaelectronvolt (GeV) energies over centimeters distances**
  - **Direct Light Acceleration**

- **Ion acceleration**
  - **Protons and ions are accelerated to megaelectronvolt (MeV) energies by a mechanism known as 'target normal sheath acceleration' (TNSA)**

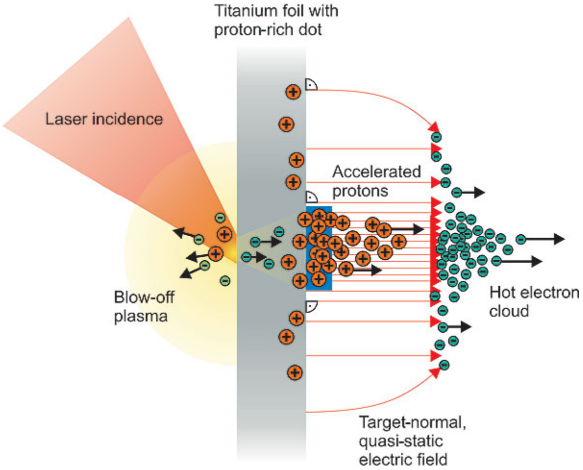
- **X-ray radiation sources**
  - **keV to MeV x-rays via non-linear Thomson Scattering**
  - **Kα monochromatic emission**
  - **Bremsstrahlung broadband radiation**

- **Neutron sources**
  - **Protons incident on a secondary target (e.g. Lithium) can produce MeV neutrons**

- **QED physics**

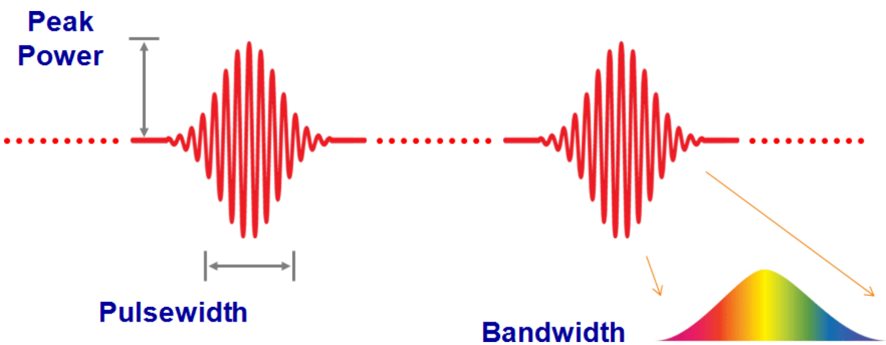


Electron density distribution and generation of quasi-monoenergetic electron bunches observed in PIC simulations.



Target Sheath Normal Acceleration: Laser acceleration of protons from the back side of a microstructured target.

Summary and outlook



The program aims to understand and control light sources exhibiting extreme temporal, bandwidth and peak power characteristics.

Optical frequency combs
ultra-wide bandwidths

- **Spectral coverage to exceed an octave with high power/comb.**
- **Coherence across EUV-LWIR.**
- **Novel resonator designs (e.g. micro-resonator based).**
- **Ultra-broadband pulse shaping.**
- **…**

High-field laser physics
high peak powers

- **Laser-solid interactions.**
- **Fs propagation in media.**
- **Sources of secondary photons.**
- **Compact particle accelerators.**
- **High peak power laser architectures.**
- **High repetition rates.**
- **New wavelengths of operation.**
- **…**

Attosecond science
ultrashort pulsewidths

- **Efficient, high-flux generation.**
- **Pump-probe methods.**
- **Probe atoms/molecules & condensed matter systems.**
- **Attosecond pulse propagation.**
- **Novel attosecond experiments.**
- **Fundamental interpretations of attosecond measurements.**
- **…**